SPACE WEATHER INTRODUCTORY COURSE

SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

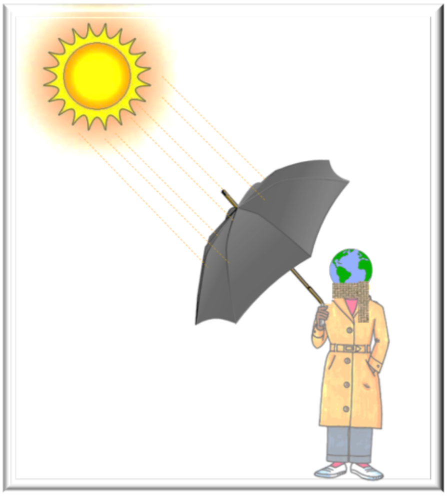
May 2017

Space weather effects

Jan Janssens

Space Weather effects (SWx effects)

- *Introduction*
- *SWx effects from*
  - *Solar flares*
  - *Proton events*
  - *ICMEs*
  - *Coronal holes*
- *Historical solar storms*
- *SC24 solar storms*



Space Weather (SWx)

- Space weather refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health.

NSWP, ESA

SWIC 2017 – Collaboration between STCE, Koninklijke Luchtmacht, KNMI

ESA: Space weather refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health.
http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/Space_Weather_-_SWE_Segment

National Space Weather Program (USA)
http://www.spaceweathercenter.org/swop/NSWP/1.html

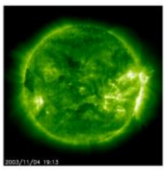
Wall of Peace
Space weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them; and also at forecasting and nowcasting the possible impacts on biological and technological systems.

Solar eruptions

Magnetic Reconnection

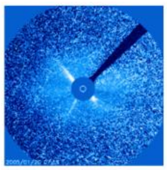
Radiation

Solar flares

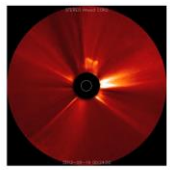


Particles

Proton events



Coronal Mass Ejections

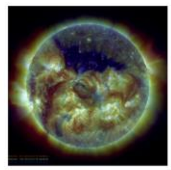


Solar corona

Solar wind

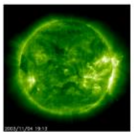
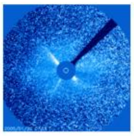
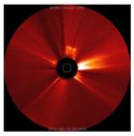
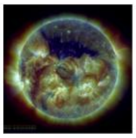
Particles

Coronal Hole



Disturbed Space weather

Causes

Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
			

	Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
Arrival	Immediately	15 min to a few hours	20 to 72+ hours	2 to 4 days
NOAA scales	R1 (minor) => R5 (extreme)	S1 (minor) => S5 (extreme)	G1 (minor) => G5 (extreme)	
Parameter	M1 => $\geq$ X20	Pfu (>10MeV): 10 => 10^5	Kp = 5 => Kp = 9	
Duration	Minutes to hours	Hours to days	Days	
Protection	Earth's atmosphere	Earth's magnetic field	Earth's magnetic field	

Effects

Radio communications	Satellites	Satellites	
Radar interference	Astronauts & Airplanes	Aurora	
	Communication/Navigation	Communication/Navigation	
	Ozone	Electrical Currents (GIC)	

Baker et al. (2016): Resource Letter SW1: Space Weather
http://adsabs.harvard.edu/abs/2016AmJPh..84..166B
http://aapt.scitation.org/doi/pdf/10.1119/1.4938403

Brekke (2016): **AGF-216 lecture 2016: Space Weather**
http://www.slideshare.net/UniSvalbard/agf216-lecture-2016-space-weather

Valtonen (2004): Space Weather: Effects on Space Technology
http://slideplayer.com/slide/3603908/

Disturbed Space weather

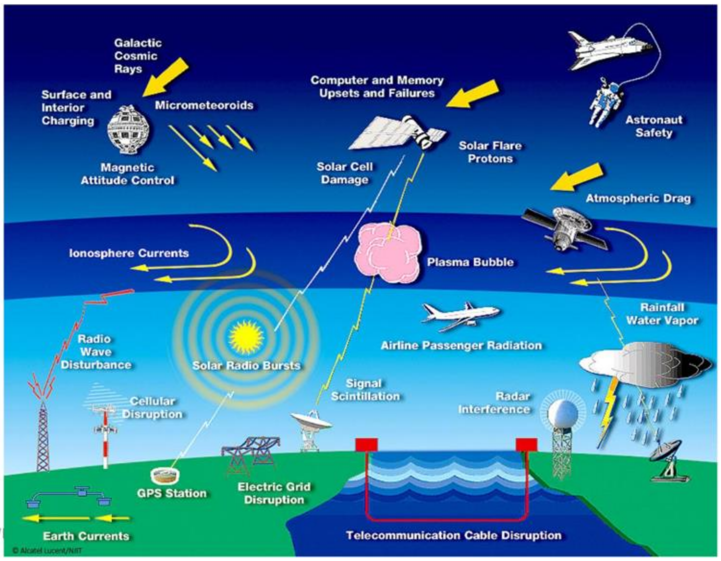


Figure from NASA: https://www.nasa.gov/mission_pages/sunearth/news/gallery/agu11-spaceweather.html

Solar flare - EM radiation
Penetration depth in Earth’s atmosphere

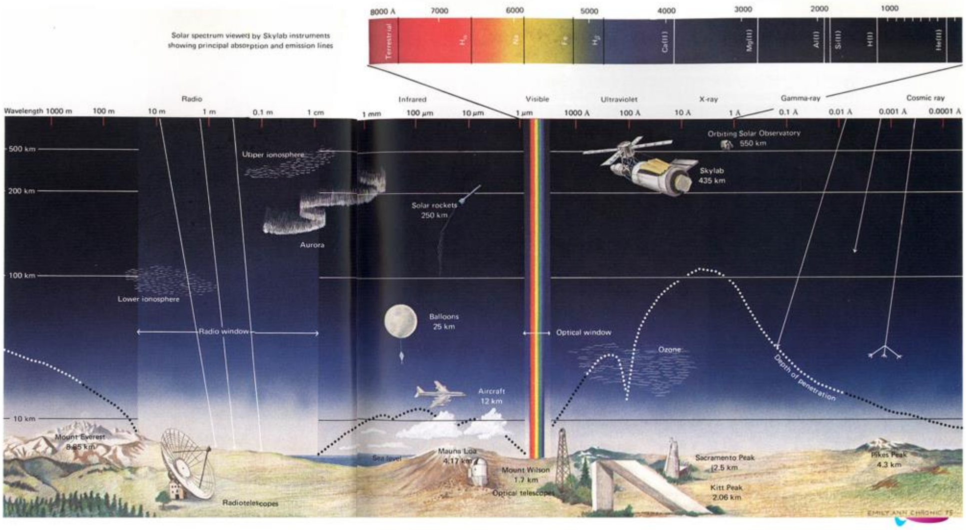


Figure at https://history.nasa.gov/SP-402/p40.htm
From the book ”A New Sun: The Solar Results from Skylab” by John A. Eddy

SPECTRUM OF SOLAR RADIATION. Visible sunlight is but one part of the total radiation Earth receives from the Sun; shown here is the full span of electromagnetic radiation from our nearest star. Electromagnetic radiation such as sunlight travels in waves, the wavelengths of which serve as descriptions, or identifiers, of the different forms of radiation. Our eyes see only a narrow band of wavelengths-the "visible spectrum" of rainbow colors from about 4000 to 7000 Å, violet to red. We see it on the chart as a rainbow of colors. To the left of the visible spectrum is the infrared, covering a wider band of wavelengths, reaching from the red of the visible to wavelengths of about 1 mm. The Sun emits light, or radiation, throughout this region. Although we cannot see it, we can feel infrared waves as heat on our skin. To the left of the infrared stretches the vast spectrum of radio wavelengths, where the Sun also emits energy that [**41**] is detectable by solar radio telescopes that "hear" it on radio receivers as a form of cosmic static. To the right of the visible spectrum stretch the shorter and more energetic wavelengths of ultraviolet radiation, X-rays, gamma rays and cosmic rays. All are invisible to our eye. These shorter, invisible wavelengths arise in the upper, more active layers of the Sun, and are thus especially valuable for the study of the active Sun. Special telescopes and sensors are required to measure the radiation at these wavelengths.

The atmosphere of Earth is transparent to visible sunlight; almost all the sunlight in the visible spectrum passes through the air to reach the surface of the ground. Gases in the terrestrial atmosphere, such as oxygen, ozone, or water vapor, absorb most of the infrared, ultraviolet, X-ray, and shorter wavelengths of solar radiation before it reaches us. On the chart Earth's atmosphere is shown in vertical cross-section, with a scale of height above sea-level at left. The depth to which each region of the solar spectrum penetrates is shown as a dotted line. In the radio region, like the visible, penetration is almost complete, and these regions are called "windows." X-ray radiation is totally absorbed far above Earth, at an altitude of about 100 km. Skylab, and other spacecraft and rockets, were at altitudes high enough to feel and observe the full range of electromagnetic radiation from the Sun-a feat impossible for solar astronomers on the ground.

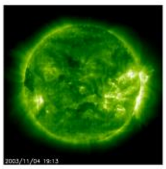
Skylab carried special telescopes to observe the Sun in the region from about 2 to 7000 Å wavelength, in X-ray, ultraviolet, and visible regions of the spectrum. Its region of observation is shown in the expanded spectrum at the top, with spectral lines of special interest as dark, vertical lines.

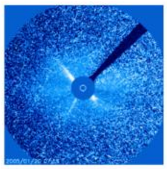
Solar eruptions — Solar corona

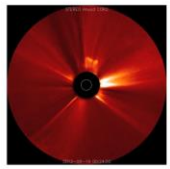
Magnetic Reconnection — **Solar wind**

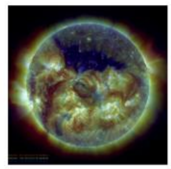
Radiation — **Particles** — **Particles**

Solar flares — **Proton storms** — **Coronal Mass Ejections** — **Coronal Hole**









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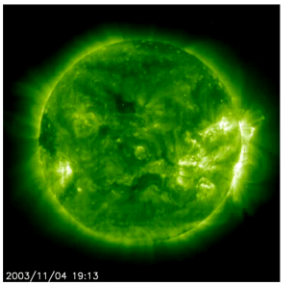
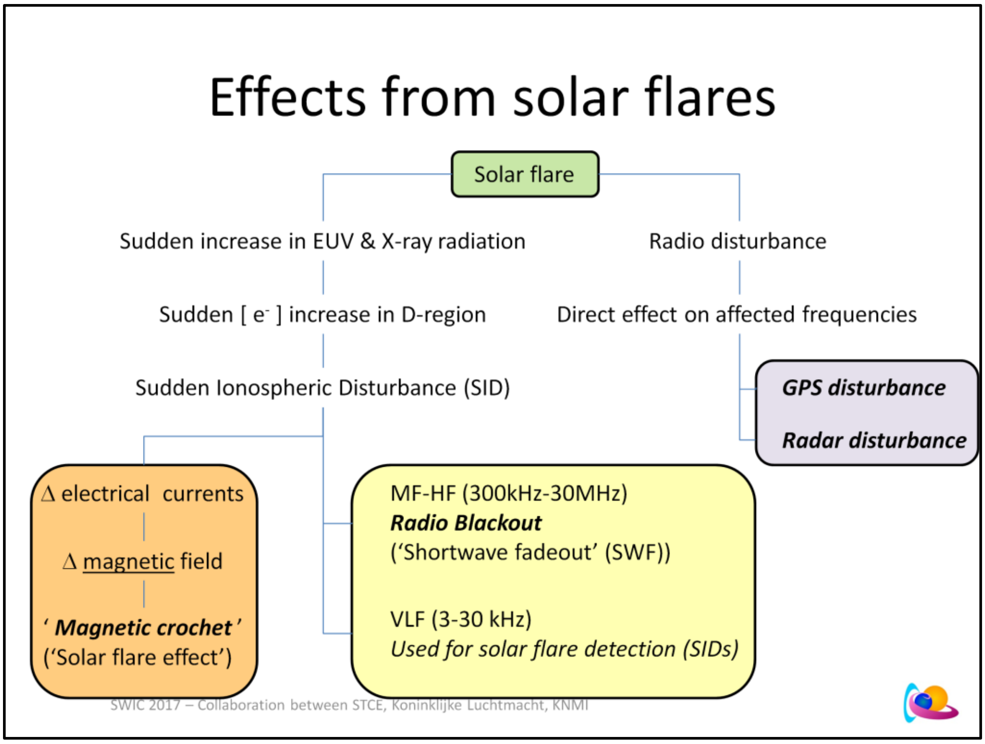
Solar flares





A very comprehensive discussion on the immediate effects from solar flares is at
NGDC: Sudden Ionospheric Disturbance
https://www.ngdc.noaa.gov/stp/space-weather/ionospheric-data/sids/documentation/readme_sudden-ionospheric-disturbances.pdf
https://www.ngdc.noaa.gov/stp/space-weather/ionospheric-data/sids/documentation/

Sudden Ionospheric Disturbance (after Wikipedia, 2014) – A sudden ionospheric disturbance (SID) is an abnormally high ionization/plasma density in the D region of the ionosphere caused by a solar flare. The SID results in a sudden increase in radio-wave absorption that is most severe in the upper medium frequency (MF) and lower high frequency (HF) ranges, and as a result often interrupts or interferes with telecommunications systems. The Dellinger effect, or Mögel–Dellinger effect, is another name for a sudden ionospheric disturbance. The effect was discovered by John Howard Dellinger around 1935 and also described by the German physicist Hans Mögel in 1930. The fadeouts are characterized by sudden onset and a recovery that takes minutes or hours. When a solar flare occurs on the Sun a blast of intense ultraviolet and x-ray radiation hits the dayside of the Earth after a propagation time of about 8 minutes. This high energy radiation is absorbed by atmospheric particles, raising them to excited states and knocking electrons free in the process of photoionization. The low-altitude ionospheric layers (D region and E region) immediately increase in density over the entire dayside. The ionospheric disturbance enhances VLF radio propagation. Scientists on the ground can use this enhancement to detect solar flares; by monitoring the signal strength of a distant VLF transmitter, sudden ionospheric disturbances (SIDs) are recorded and indicate when solar flares have taken place.
Short wave radio waves (in the HF range) are absorbed by the increased particles in the low altitude ionosphere causing a complete blackout of radio communications. This is called a short-wave fading. These fadeouts last for a few minutes to a few hours and are most severe in the equatorial regions where the Sun is most directly overhead. The ionospheric disturbance enhances long wave (VLF) radio propagation. SIDs are observed and recorded by monitoring the signal strength of a distant VLF transmitter. SIDs are classified in a number of ways including; ShortWave Fadeouts (SWF), Sudden Cosmic Noise Absorption (SCNA), Sudden Enhancement of Atmospherics (SEA/SDA), Sudden Phase Anomalies (SFA), Sudden Enhancements of Signal (SES), Sudden Field Anomalies (SFA) and Sudden Frequency Deviations (SFD).

Effects from solar flares

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

Info at:
http://www.swpc.noaa.gov/noaa-scales-explanation
SWPC: http://www.swpc.noaa.gov/phenomena/solar-flares-radio-blackouts
SWS: http://www.sws.bom.gov.au/Educational/1/3/5

Zhang et al. (2011): Impact factor for the ionospheric total electron content response to solar flare irradiation
http://onlinelibrary.wiley.com/doi/10.1029/2010JA016089/full
As one of the fastest and severest solar events, the solar flare, which is mainly classified according to the peak flux of soft X-rays in the 0.1–0.8 nm region measured on the GOES X-ray detector, has a great influence on the earth upper atmosphere and ionosphere. During a flare, the extreme ultraviolet (EUV) and X-rays emitted from the solar active region ionize the atmospheric neutral compositions in the altitudes of ionosphere to make the extra ionospheric ionization that causes many kinds of sudden ionospheric disturbance phenomenon (SID), which are generally recorded as sudden phase anomaly (SPA), sudden cosmic noise absorption (SCNA), sudden frequency deviation (SFD), shortwave fadeout (SWF), solar flare effect (SFE) or geomagnetic crochet, and sudden increase of total electron content (SITEC) [*Donnelly*, 1969; *Mitra*, 1974].

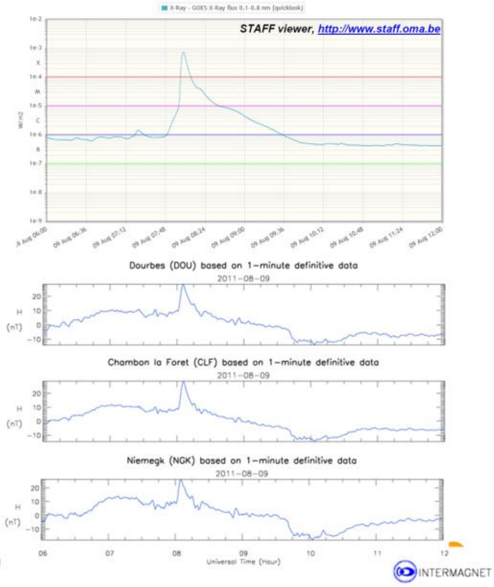
Effects from solar flares

- Solar flare effect (SFE)
  - « Magnetic crochet »
  - Immediate change in magnetic field strength due to a strong & fast solar flare (dayside)
    - Sudden ionization ionosphere
    - 14 nT @ mid-latitudes
  - Thresholds
    - H-alpha: 2B (30%)
    - X-ray: X1 (50%)
  - Quite rare

TABLE 1

Outstanding solar flare effects at mid-latitudes identified in a literature search for events from 1936–1968 and from associations with >X10 soft X-ray flares, 1984–2003.

Date	1–8 Å Class	Magnetometer station	Zenith angle (°)	SFE amplitude (nT)
04 Nov. 2003	X28	Newport	63	115
28 Feb. 1942	–	Eskdalemuir	63	112
28 Oct. 2003	>X17	Tamanrasset	36	111
01 Sep. 1859	–	Greenwich	44	110
15 Jun. 1991	>X12	Hyderabad	22	95
06 Jun. 1991	>X12	Guam	20	90
15 Apr. 2001	>X15	Tamanrasset	34	85

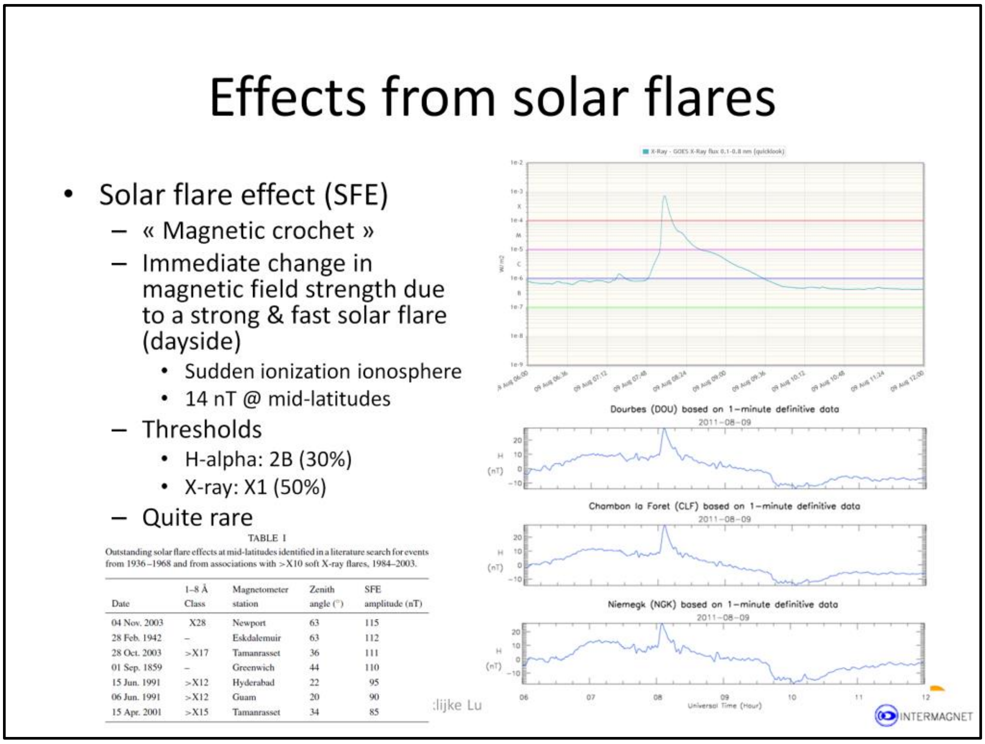


Curto et al. (2009): Geoeffectiveness of solar flares in magnetic crochet (sfe) production: I—Dependence on their spectral nature and position on the solar disk - http://adsabs.harvard.edu/abs/2009JASTP..71.1695C

Radiations have a prompt effect on Earth by ionizing the upper layers of the atmosphere(Svestka,1976; Vermaetal.,1987). Solar flare effects (sfe, also called magnetic crochets) are events directly related to an enhancement in the solar radiation that produces an increase in the electric conductivity and currents in the ionosphere, and finally a magnetic signature at ground level (Curto et al.,1994b).

From the point of view of the radiations, the percentage of H-alpha flares producing sfe events is 30%, so approximately only one out of three of the significant Ha flares registered over the period 1975–1989 produced an observable geomagnetic effect. 52% out of them were at the same time associated to a strong X-ray emission. For the case of the X-ray flares the percentage is: 50%. That is, half of the significant X-ray flares produce a sfe. Therefore, X-flares are more efficient than Ha flares in producing sfe events.

Curto et al. (2009): Geoeffectiveness of solar flares in magnetic crochet (sfe) production: II—Dependence on the detection method http://adsabs.harvard.edu/abs/2009JASTP..71.1705C



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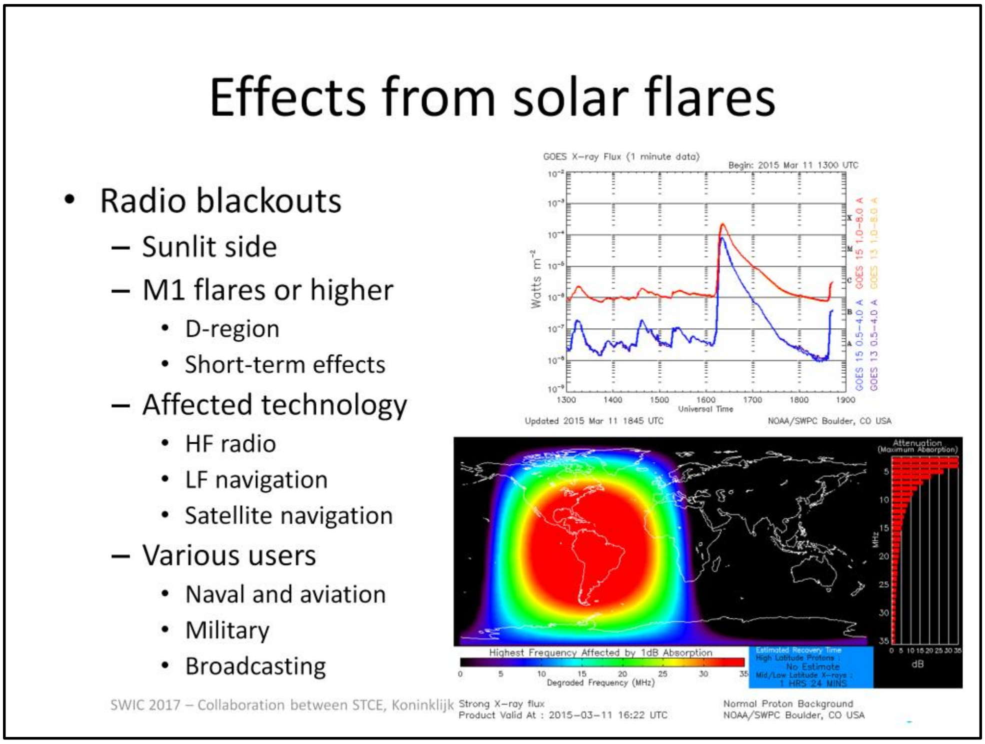
Curto et al. (2016): Sfe: waiting for the big one
http://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150071.pdf
Solar flare effects (Sfe) are rapid magnetic variations which are related to the enhancement of the amount of radiation produced during Solar flare events (Curto et al. 1994a). X-ray and EUV emissions are the main electromagnetic radiation which cause variations on the electronic density in the ionospheric layers. From the F to the D regions, there are electron density enhancements during solar flares and on Earth the magnetic signature of a flare is visible in the illuminated hemisphere. Interest in the occurrence and frequency of solar flares has increased in the field of Space Weather because of the perturbations they produce on these variables – the electron density in the ionosphere or the earth's magnetic field. Both of these are used either actively or passively by key technological systems such as the GPS positioning/guidance system, HF communications, satellite communications, etc. (Lanzerotti 1979, 1983). The impact of severe Space Weather events on domestic and international networks can lead to huge economic costs (Cannon 2013; Schulte in den Bäumen et al. 2014).

More info at the Australian SWS: http://www.sws.bom.gov.au/Educational/3/1/1

Table taken from Cliver at al. (2004): The 1859 Solar-Terrestrial Disturbance And the Current Limits of Extreme Space Weather Activity
http://adsabs.harvard.edu/abs/2004SoPh..224..407C

A good example from this solar cycle (SC24) was the 5 November 2013 event (X3 flare in NOAA 1890 at 22:12UT).
See Intermagnet at http://www.intermagnet.org/data-donnee/dataplot-eng.php for plots (Pamatai, Honolulu) for plots of H.

Live and listings e.g. at http://www.obsebre.url.edu/en/rapid



Kumar et al. (2014): Space weather effects on the low latitude D-region ionosphere during solar minimum
http://adsabs.harvard.edu/abs/2014EP%26S...66...76K
The solar flares and geomagnetic storms are the phenomena associated with the space weather. The solar flares, particularly with X-ray having wavelengths typically of tenths of a nanometer, penetrate the D-region of the ionosphere and increase the electron density via extra ionization (e.g. Mitra 1974). The increase in the D-region electron density can produce significant perturbations in the received phase and amplitude of VLF signals propagating in the Earth ionosphere waveguide (EIWG). The normal unperturbed daytime D-region from which VLF signals are usually reflected is maintained mainly by direct Lyman-α radiation (121.6 nm) from the sun that partially ionizes the minor neutral constituent nitric oxide (at a height around 70 km). Under normal conditions, the solar X-ray flux is too small to be a significant source for ionizing the D-region; however, when a solar flare occurs, the X-ray flux from the sun increases dramatically. The X-ray flux with wavelengths appreciably below 1 nm penetrates down to the D-region and markedly increases the ionization rate of the neutral constituents particularly nitrogen and oxygen hence increases the D-region electron density.

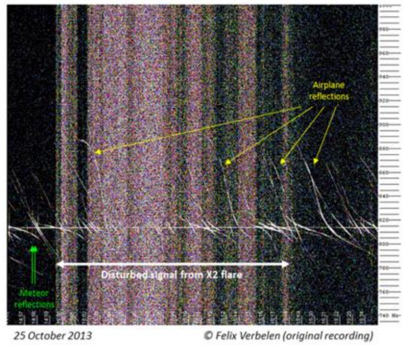
More info at:
SWPC: http://www.swpc.noaa.gov/phenomena/solar-flares-radio-blackouts
SWS: http://www.sws.bom.gov.au/Educational/1/3/5

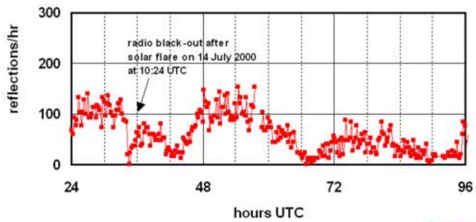
Realtime charts on affected areas at http://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap

Example from STCE: http://www.stce.be/news/299/welcome.html

Effects from solar flares

- Radio blackouts
  - Main users HF (Wiki):
    - Military and governmental communication systems
    - Aviation air-to-ground communications
    - Amateur radio
    - Shortwave international and regional broadcasting
    - Maritime sea-to-shore services
    - Over-the-horizon radar systems
    - Global Maritime Distress and Safety System (GMDSS) communication





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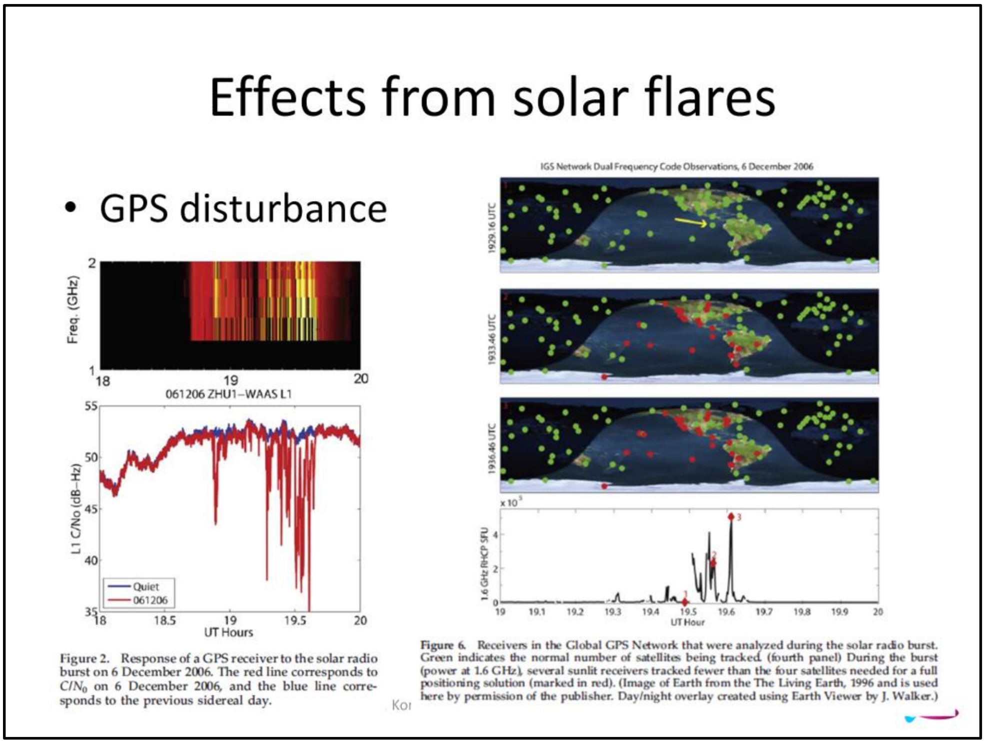
List of users from Wiki: https://en.wikipedia.org/wiki/High_frequency

Chart with meteor counts from the Dutch radio/meteor section.

Chart with radio disturbance from STCE: http://www.stce.be/news/222/welcome.html

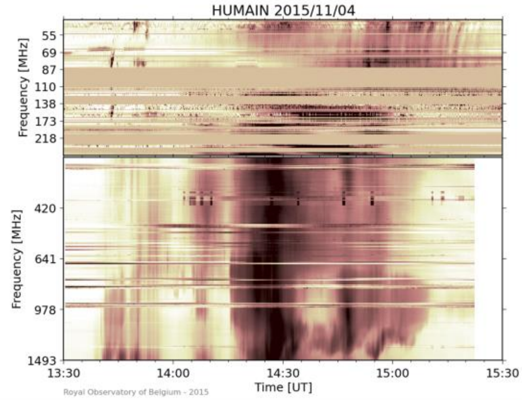


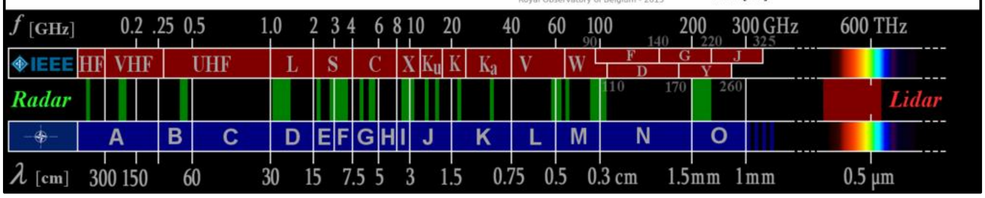
Cerruti at al. (2008): Effect of intense December 2006 solar radio bursts on GPS receivers
http://adsabs.harvard.edu/abs/2008SpWea...610D07C
Solar radio bursts during December 2006 were sufficiently intense to be measurable with GPS receivers. The strongest event occurred on 6 December 2006 and affected the operation of many GPS receivers. This event exceeded 1,000,000 solar flux unit and was about 10 times larger than any previously reported event. The strength of the event was especially surprising since the solar radio bursts occurred near sola r minimum. The strongest periods of solar radio burst activity lasted a few minutes to a few tens of minutes and, in some cases, exhibited large intensity differences between L1 (1575.42 MHz)
and L2 (1227.60 MHz). Civilian dual frequency GPS receivers were the most severely affected, and these events suggest that continuous, precise positioning services should account for solar radio bursts in their operational plans. This investigation raises the possibility of even more intense solar radio bursts
during the next solar maximum that will significantly impact the operation of GPS receivers.

Figures taken from the Cerruti paper

Effects from solar flares

- Radar disturbance
  - 4 November 2015
    - M3 flare paralyzes Swedish air traffic
  - Seems to require a set of special conditions





On 4 November, NOAA 2443 produced an M3.7 flare peaking at 13:39UT. This at first sight very normal flare was associated with strong radio and ionospheric disturbances that also affected radar and GPS frequencies. As a result, Swedish air traffic was halted for about an hour during the afternoon. The air traffic problems started at the most intense phase of the radio storm, and followed right on the heels of a minor geomagnetic storm caused by the high speed stream of a coronal hole. The CME associated with the M3 flare would cause a moderate (Kp = 6) geomagnetic storm during the first half of 7 November.

See also STCE news item at http://www.stce.be/news/326/welcome.html
and http://www.cbc.ca/news/technology/solar-storm-sweden-1.3304271
and https://phys.org/news/2015-11-sweden-solar-flare-flight.html

During the ESWW12, it was communicated that signals from some GPS satellites were affected (degradation), but that there was always a sufficient number of satellites available to assure a properly operating GPS service.

A full discussion of this event:
Opgenoorth et al. (2016): Solar activity during the space weather incident of Nov 4., 2015 - Complex data and lessons learned
adsabs.harvard.edu/abs/2016EGUGA..1812017O
During the afternoon of November 4, 2015 most southern Swedish aviation radar systems experienced heavy disturbances, which eventually forced an outing of the majority of the radars. In consequence the entire southern Swedish aerospace had to be closed for incoming and leaving air traffic for about 2 hours. Immediately after the incident space weather anomalies were made responsible for the radar disturbances, but it took a very thorough investigation to differentiate disturbances from an ongoing magnetic storm caused by earlier solar activity, which had no disturbing effects on the flight radars, from a new and, indeed, extreme radio-burst on the Sun, which caused the Swedish radar anomalies.

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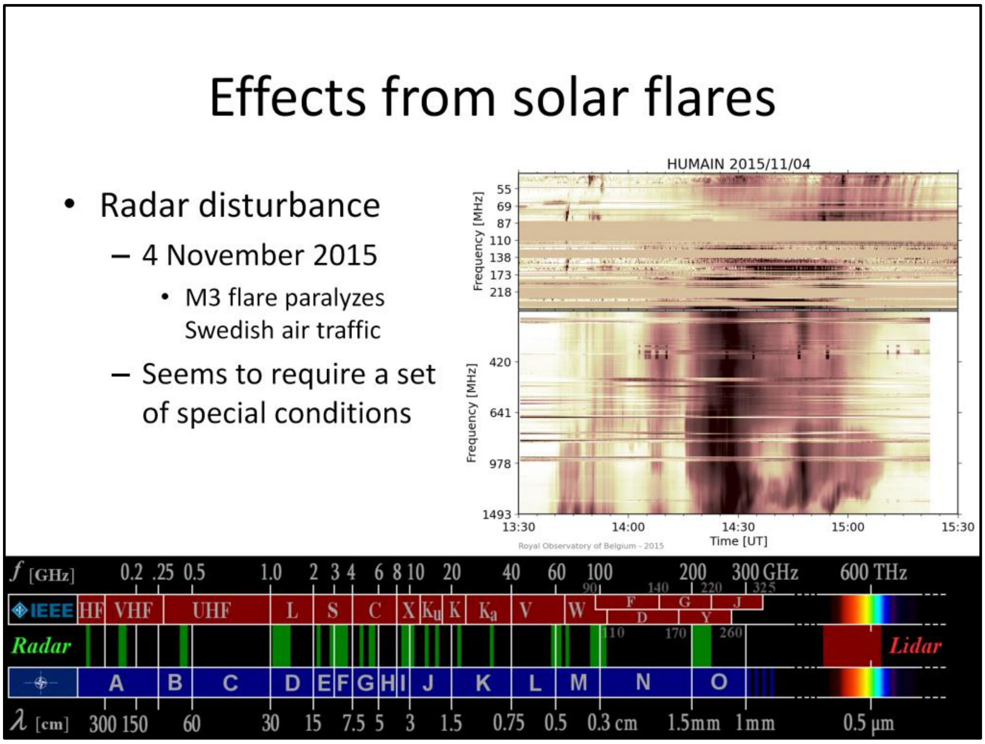

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Other systems in various European countries also experienced major radio-disturbances during this extreme event, but they were not of the gravity as experienced in Sweden, or at least not causing a similar damage. One of the problems in reaching the right conclusions about the incident was that the extreme radio-burst around 1400 UT on Nov 4 (more than 50000 SFU at GHz frequencies), emerged from a medium size M3.7 Flare on the Sun, which did not trigger any immediate warnings. We will report about the analysis leading to the improved understanding of this extreme space weather event, evaluate the importance of solar radio observations, and discuss possible mitigation strategies for future events of similar nature.

Radar figure taken from http://www.radartutorial.eu/07.waves/Waves%20and%20Frequency%20Ranges.en.html

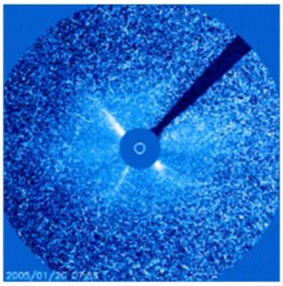
Unofficial communications (On 5 November 2015):
The radar was probably disturbed by reflections from ionospheric irregularities in the E region arising from strong electric fields causing plasma instabilities (Farley-Buneman). The irregularities are field-aligned and located in the auroral zone. Then (Bragg-type) reflection is possible for radio waves originating from south, i.e. southern Sweden to northern Germany. The waves are reflected back to south, where they disturb reception of the normal signals from e.g. airplane transponders. The phenomenon is known since the 60-ties as "radio aurora" among radio amateurs and did also affect sometimes the analogue TV reception. Mainly VHF is known to be affected. The SPIDER rocket to be launched beginning of 2016 from ESRANGE is for investigating this particular auroral phenomenon.
…
There was an incident very much likes this about ten years ago, at a much more important airport: Frankfurt. They halted all air traffic taking off for half an hour, because the solar emission produced 'ghost signals' in their radars and there suddenly seemed to be airplanes everywhere. This incident was, as far as I know, never officially reported, but Eurocontrol knows about it (which is where I got it from).

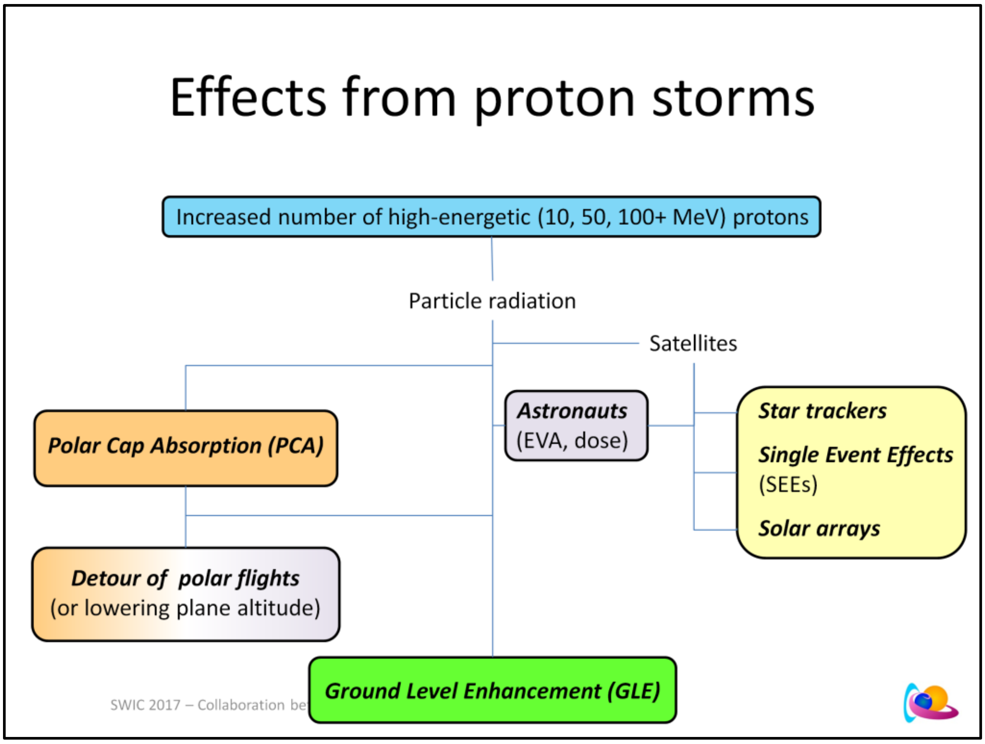
More on radio aurora at https://www.ursa.fi/ursa/jaostot/revontulet/radio/enradio.html

Space Weather effects (SWx effects)

- *Introduction*
- ***SWx effects from***
  - *Solar flares*
  - ***Proton events***
  - *ICMEs*
  - *Coronal holes*
- *Historical solar storms*
- *SC24 solar storms*

Proton events





EVA: Extra-Vehicular Activity

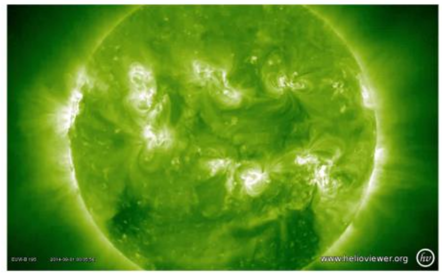
Effects from proton storms

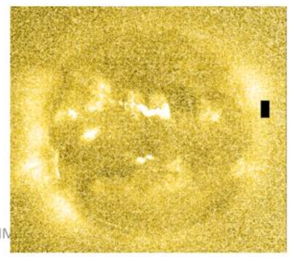
Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

More info at
SWPC: http://www.swpc.noaa.gov/noaa-scales-explanation
SWPC: http://www.swpc.noaa.gov/phenomena/solar-radiation-storm

Effects from proton storms

- Satellites
  - Star trackers
    - Spacecraft orientation
    - Photonics noise
      - Proton « impacts »
        - » True stars?
      - Misorientation
        - » Solar panels
          - No energy
        - » Loss sun-lock
      - Data loss
        - » Gravity Probe-B





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Baker et al. (2016): Resource Letter SW1: Space Weather
http://adsabs.harvard.edu/abs/2016AmJPh..84..166B
http://aapt.scitation.org/doi/pdf/10.1119/1.4938403
… Satellites can be oriented by the use of star sensors (and Sun sensors). For example, scientific satellites in orbit around Earth may need to know the Sun direction for use in interpreting data from on-board scientific instruments. Star sensors are used for scientific astronomical satellites, as well as for national security and other civil satellite purposes, such as communications. Charged particle radiation can produce false signals in the optical sensors, thus confusing the electronics—with resulting confusion of the orientation. In regions of intense radiation, such as during intervals of enhanced Van Allen belt radiation within Earth's magnetosphere, and during large solar particle events outside the magnetosphere, star and Sun sensors can be severely compromised. The design of attitude control systems usually includes automatic safing procedures as the principal mitigation action.

A good example of a proton storm induced orientation problem was on 1 September 2014 with ST-B.
See the news item at http://www.stce.be/news/266/welcome.html
https://sohowww.nascom.nasa.gov/pickoftheweek/old/05sep2014/
A far-side powerful flare erupted and triggered a huge and long-lasting proton storm that flew past the STEREO Behind spacecraft on Labor Day, Sept. 1, 2014. The storm was so strong that it temporarily confused the star trackers on both STEREO spacecraft. The "snowstorm effect" that you see was caused by high-energy particles hitting the spacecraft's detectors in the SECCHI instrument's extreme ultraviolet and inner coronagraph telescopes' (EUVI and COR1). The moment when the star tracker on Behind resets is evident when the spacecraft starts rolling. The spacecraft uses SECCHI's guide telescope to keep locked on the Sun, but depends on the star tracker to determine its roll angle. Once the star tracker came back online, the spacecraft almost immediately moved back to its correct orientation.

Gravity Probe B: https://en.wikipedia.org/wiki/Timeline_of_Gravity_Probe_B
January 2005 - A series of strong solar flares disrupted data taking for several days. On January 17 a very powerful radiation storm created multi-bit errors in the onboard computer memory, and saturated the telescope detectors so that *GP-B* lost track of the guide star. The science team, however, is confident that the temporary loss of science data will have no significant effect on the results. On January 20 the high level of proton flux was still generating "single bit errors" in *GP-B* memory, but the telescope is locked on the guide star again, and the gyroscope electronics seem to perform nominally.

Effects from proton storms

- Satellites
  - Single Event Effect (SEE)
    - Direct hit of an electronic component by an energetic particle resulting in an anomaly
    - Several variations
      - SEU (bit flip), SEL, SEB,…
    - Sources
      - Cosmic Rays
        - » DSCOVR
      - Solar proton storms
      - Radiation belts

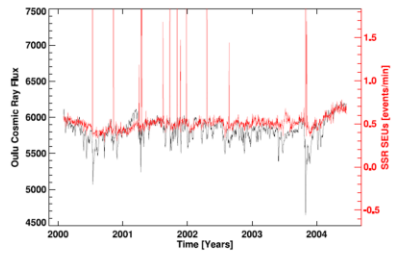
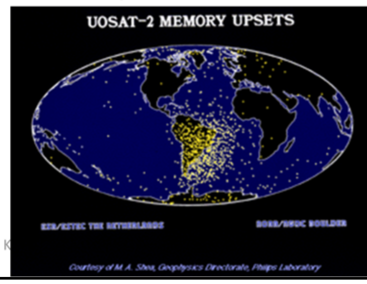


Figure 3: Subset of the data in Fig. 1 during solar maximum. The plot shows a dozen sharp spikes on top of the solar-cycle-modulated background of SSR SEUs triggered by cosmic ray hits. These spikes are caused by isolated strong SEP events. Most of them coincide with a CRF down spike.



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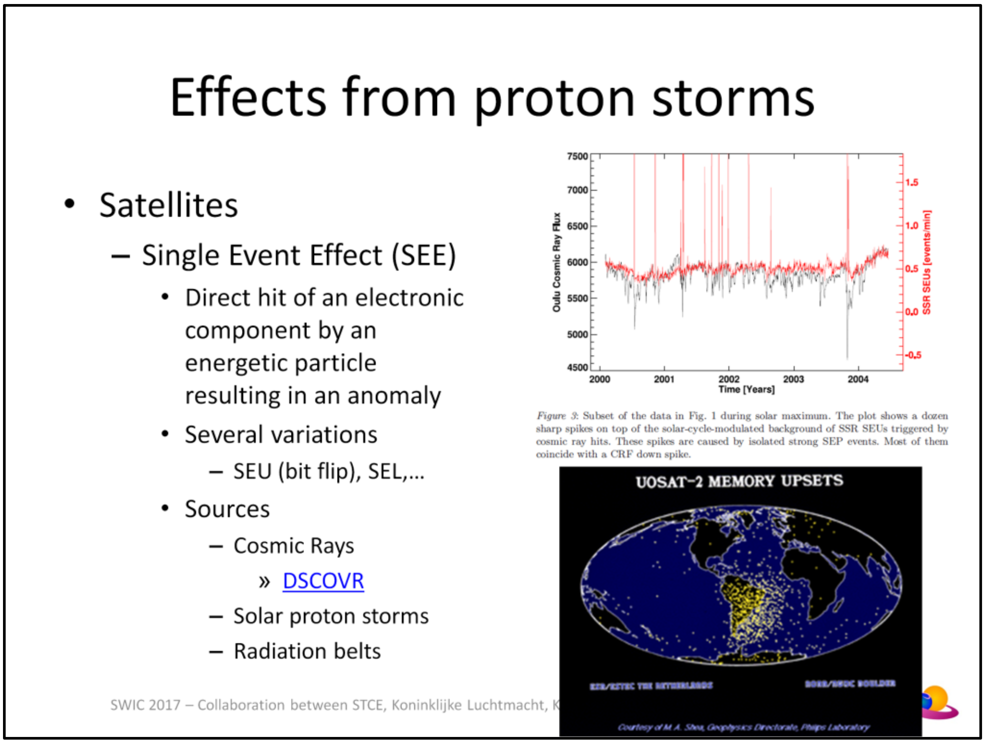
Top Figure from Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
http://adsabs.harvard.edu/abs/2015CEAB...39..109C (Figure 3)

Galvan et al. (2014): Satellite Anomalies
http://www.rand.org/content/dam/rand/pubs/research_reports/RR500/RR560/RAND_RR560.pdf
Single Event Effects (SEEs) - SEEs are anomalies caused not by a gradual buildup of charge over time as with surface or internal charging, but by the impact of a single high-energy charged particle into sensitive electronic components of a satellite subsystem, this single event causing ionization and an anomaly. They typically occur because of high-energy (> 2 MeV) protons and electrons striking memory devices in the spacecraft's electronics systems, causing the spacecraft (or a subsystem) to halt operations, either temporarily or permanently (e.g., Speich and Poppe, 2000).
SEEs include "bit flips" or SEUs, where a high-energy particle imparts its charge to a solid-state memory device, causing errors in the system software, which may or may not damage hardware and can potentially be detected and repaired with error-detection-and-correction algorithms (EDACs) in the system software. One example of an EDAC is triple-modular redundancy (TMR), in which three processors perform the same calculations in parallel and then compare their answers. If one processor's answers differ from those of the other two, the "correct" two would outvote the incorrect one, and the third processor system could be rebooted or otherwise corrected, and the subsystem in general continues to operate.4 Other types of SEEs include single-event latchups (SELs), in which a subsystem hangs/crashes as a result of a high-energy particle impact. This causes the subsystem to draw excess current from the power supply, and the device must be turned off and then back on to be operable. Sometimes SEL can lead to destruction of the device if the excess drawn current is too high for the power supply. In this case, the SEE is referred to as single-event burnout (e.g., Wertz and Larson, 1999). Susceptibility to SEEs depends strongly on system design, and the risk is higher for satellites spending time in the Van Allen radiation belts or at GEO where there is a higher fluence of galactic cosmic rays and high-energy protons from Solar Proton Events (e.g., Mikaelian, 2001; Wertz and Larson, 1999;).

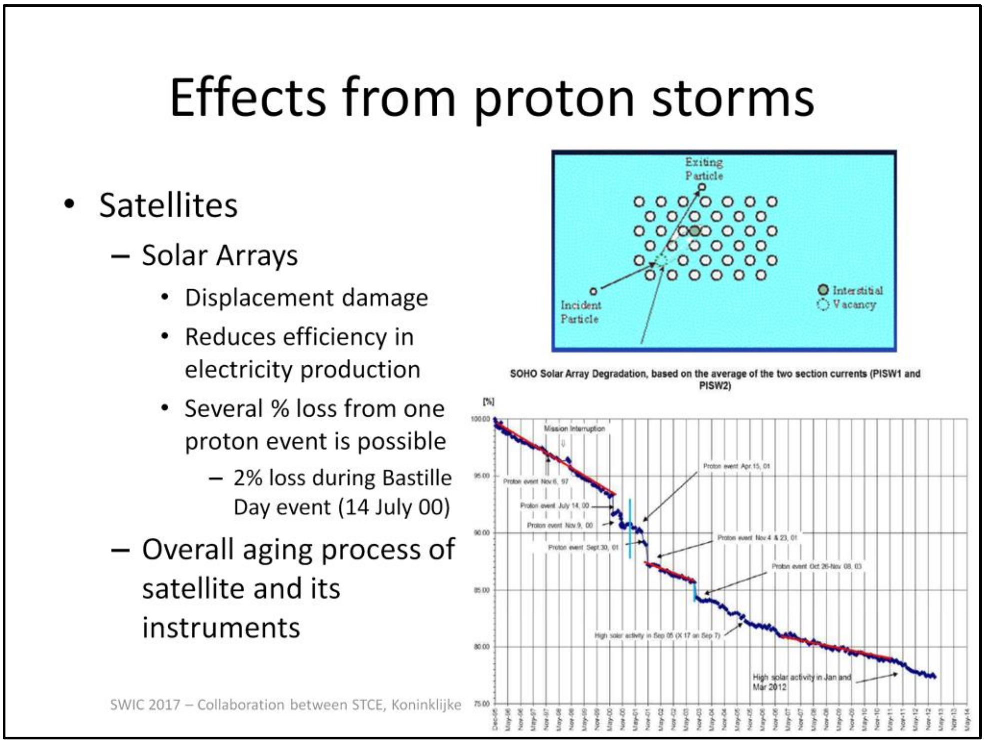
A good overview of the various SEE is in
Autran and Munteanu (2015) : Soft errors: from particles to circuits
http://s1.nonlinear.ir/epublish/book/SOFT_ERRORS_FROM_PARTICALES_TO_CIRCUITS_9781466590847.pdf (Fig. I.1)



Top Figure from Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
http://adsabs.harvard.edu/abs/2015CEAB...39..109C (Figure 3)

From: NOAA: Halloween Space Weather Storms of 2003
http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf
CHIPS – The satellite computer went offline on 29 October and contact was lost with the spacecraft for 18 hours (loss of 3-axis control because its Single Board Computer (SBC) stopped executing). When contacted, the spacecraft was tumbling, but recovery was successful. It was offline for a total of 27 hrs.

Barbieri et al.: October--November 2003's space weather and operations lessons learned
http://onlinelibrary.wiley.com/doi/10.1029/2004SW000064/epdf
Sometimes, though the effect was undesirable and serious, it was accommodated in the mission's design: The effect was a consequence that may be considered acceptable in terms of the mission's risk tolerance. For example, the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) flies a single-board computer (SBC) that is not very radiation hardened and so is built to recover autonomously, which it occasionally has to do because of the South Atlantic Anomaly. (The South Atlantic Anomaly is the region where Earth's inner van Allen radiation belt makes its closest approach to the planet's surface. For a
given altitude the radiation intensity is higher over this region than elsewhere. It is produced by a "dip" in the Earth's magnetic field at that location, caused by the fact that the center of Earth's magnetic field is offset from its geographic center by 450 km. The South Atlantic Anomaly is of great significance to satellites and other spacecraft that orbit at several hundred kilometers altitude and at orbital inclinations between 35 and 60; these orbits take satellites through the anomaly periodically, exposing them to several minutes of strong radiation each time. The International Space Station, orbiting with an inclination of 51.6, required extra shielding to deal with this problem). On 29 October the CHIPS SBC experienced a problem it could not recover from autonomously because it stopped executing. With the computer off-line the attitude control system was no longer able to maintain three-axis control, and CHIPS began tumbling. The flight operations team (FOT) responded to the anomaly by sending commands to reset the SBC, and the mission continued.

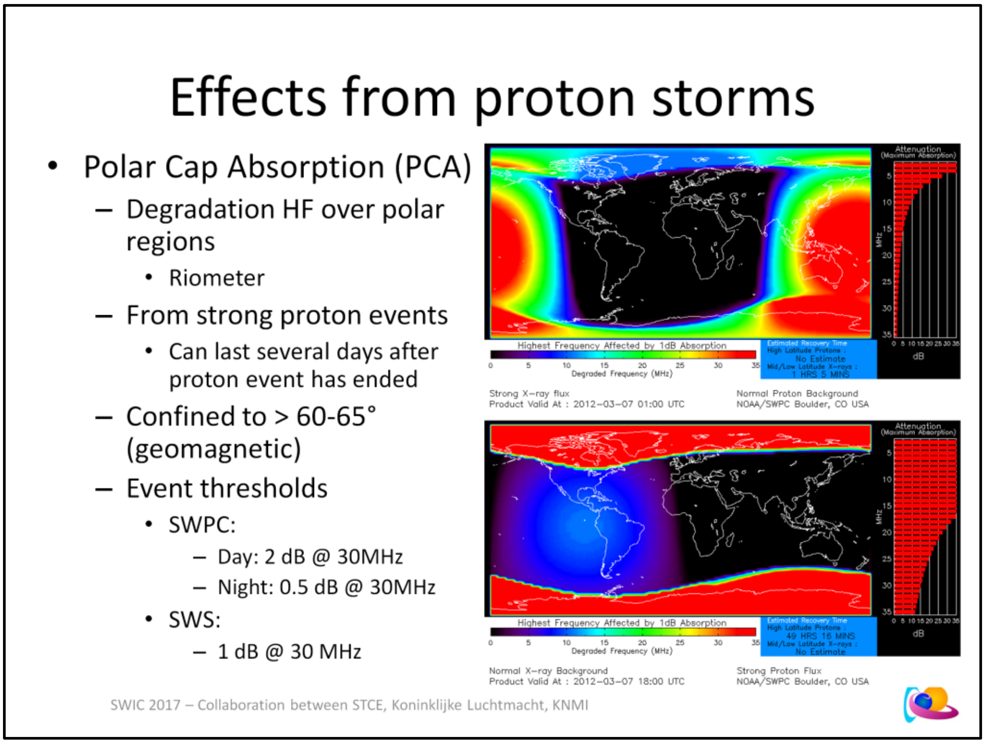


Top figure taken from Valtonen (2004): Space Weather: Effects on Space Technology
http://slideplayer.com/slide/3603908/ (slide 33)

Bottom figure taken from Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
http://adsabs.harvard.edu/abs/2015CEAB...39..109C (Figure 5)
Fig. 5 shows the degradation of the solar array efficiency from Dec 1995 until Feb 2013. The total loss was ~22.5% during that time (and has reached 24% at the end of 2014). The degradation starts with a linear, continuous decrease of 0.00368% / d (1.344% per year) from launch to Jul 2000. We attribute this decrease to the CRF (Cosmic Ray Flux) during SOHO's first solar minimum. Then follows a phase of several stepwise decrements that can be associated to SEP events during the maximum of cycle 23 around 2001. Here, individual proton events start to dominate the scene. Later follow two more episodes with continuous — but less steep — decrease. Around 2002, the degradation rate is 0.00284% / d (from a starting point of 87.2%) and only 0.00168% / d (from a starting point of 82.1%) during the period from Feb 2007 to May 2011. There is no evidence for a significant solar cycle variation. It seems as if a continuous decrease of the degradation rate reduces the value by almost a factor of two. ... We speculate that in the solar arrays cells of different radiation hardness are found and that destruction of less-radiation hard cells is in progress all the time. Also, ageing effects of the cover-glass could be responsible for efficiency loss. We tried to quantify the effects of cosmic rays and the effects of SEPs during this period. In total, of the 22.5% power loss 8.5% can be attributed to proton events. Hereof, 5% occurred during a period of only 1.5 years. Altogether, 38% ± 2% of the degradation during 17 years can be attributed to proton events. In other words: the effect of a series of violent short-term events on the solar panels is comparable to the accumulated effect of the CRF over this period.

Another nice example of solar array degradation is in Hubner et al. (2012): INTEGRAL revisits Earth - Low perigee effects on spacecraft components
http://arc.aiaa.org/doi/abs/10.2514/6.2012-1291272

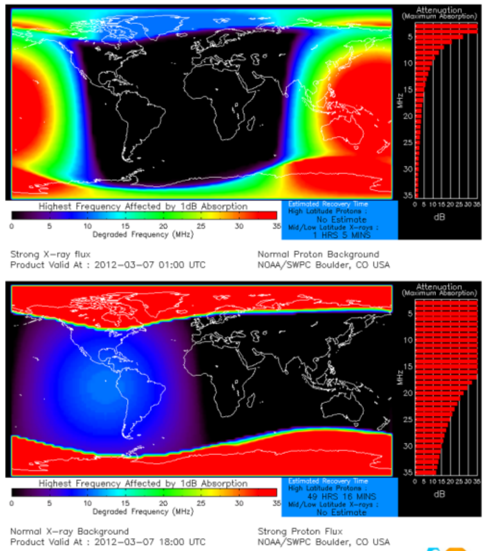
Some interesting statistics on solar array degradation provided by Intelsat:
http://www.intelsat.com/tools-resources/library/satellite-101/space-weather/



Perrone et al. (2004): **Polar cap absorption events of November 2001 at Terra Nova Bay, Antarctica**
http://adsabs.harvard.edu/abs/2004AnGeo..22.1633P
The occurrence of SPE during minimum solar activity is very low, while in active Sun years, especially during the falling and rising phase of the solar cycle, the SPEs may average one per month. It is well recognized that these solar particles have prompt and nearly complete access to the polar atmosphere via magnetic field lines interconnected between the interplanetary medium and the terrestrial field (van Allen et al., 1971). Consequently, they cause excess ionisation in the ionosphere, particularly concentrated in the polar cap, which, in turn, leads to an increase in the absorption of HF radio waves, termed polar cap absorption (PCA).
The ionisation occurs at various depths which depends on the incident particle energies, so that the ionisation in the D-region during PCA events is due mainly to protons with energy in the range of 1 to 100MeV that corresponds to an altitude between 30–80 km (Ranta et al., 1993; Sellers et al., 1977; Collis and Rietveld, 1990; Reid, 1974). Particles with even greater energies (>500 MeV) are recorded on the ground by a cosmic-ray detector; these events are called Ground Level Enhancement (GLE) (Davies, 1990).
The major PCA events are associated with solar flares located on the side of the solar central meridian towards which the Sun rotates, that is, on the west side. It has also been found that the delay between flare outbreak and the start of a PCA depends mainly upon the heliographic latitude (Ranta et al., 1993). The boundary of the PCA region is typically between 60 and 65 geomagnetic latitude, while the durations of PCAs vary from a few hours to many days (Collis and Rietveld, 1990). A characteristic feature of PCA events is the large difference between day and night absorption intensities for constant precipitating fluxes of solar particles. A day-to-night ratio in absorption intensities of around 4–8 is often observed during PCA events (Stauning, 1996; Hargreaves et al., 1993; Ranta et al., 1995; Pietrella et al., 2002). The most plausible explanation is a drastic increase in the effective recombination rate after sundown, i.e. when negative ions can exist and positive ions are mostly in the form of clusters which have much larger recombination rates than molecular ions usually found at higher altitudes, and during the day lowering the density of free electrons which cause ionospheric absorption.

Effects from proton storms

- Polar Cap Absorption (PCA)
  - Degradation HF over polar regions
    - Riometer
  - From strong proton events
    - Can last several days after proton event has ended
  - Confined to > 60-65° (geomagnetic)
  - Event thresholds
    - SWPC:
      - Day: 2 dB @ 30MHz
      - Night: 0.5 dB @ 30MHz
    - SWS:
      - 1 dB @ 30 MHz



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Speculations that the particles causing PCA were protons of solar origin were suggested before they could be verified by in situ experiments (Reid and Collins, 1959). Modern instruments carried on geostationary satellites are now able to provide continuous measurements of solar particles fluxes and
their energy spectra. Routine monitoring of ionospheric absorption is possible since the riometric technique was introduced (Little and Leinbach, 1959). This instrument measures the amount of cosmic noise absorbed by the ionosphere at operating frequencies in the range 20–50 MHz.

More info at:
Hargreaves (2005): A new method of studying the relation between ionization rates and radio-wave absorption in polar-cap absorption events
http://adsabs.harvard.edu/abs/2005AnGeo..23..359H
Polar-cap absorption events (PCA), several good examples of which have occurred during the recent solar maximum, are a direct consequence of energetic protons emitted from an active region of the Sun. On penetrating into the terrestrial atmosphere they enhance the ionization of the mesosphere, which in turn increases the absorption of radio waves in the HF and VHF bands (Bailey, 1959). The incidence and intensity of the event may conveniently be monitored in terms of the radio absorption, using a riometer (Relative Ionospheric Opacity Meter – Little and Leinbach, 1959). The proton fluxes are also routinely monitored above the atmosphere using satellite-borne detectors. An important characteristic of solar proton events is their relative uniformity over the polar regions down to a cut-off latitude at or near 60 geomagnetic latitude (Reid, 1974). The enhancement of electron density may in principle be measured as a function of height by incoherent-scatter radar.

Rose et al. (1962): The Polar Cap Absorption Effect
http://adsabs.harvard.edu/abs/1962SSRv....1..115R

A description of another PCA is in Liu et al. (2001): Responses of the polar ionosphere to the Bastille Day solar event
http://adsabs.harvard.edu/abs/2001SoPh..204..305L
A description of another PCA is in Bieber et al. (2005): Largest GLE in Half a Century: Neutron Monitor Observations of the January 20, 2005 Event
http://neutronm.bartol.udel.edu/reprints/2005bieber.pdf

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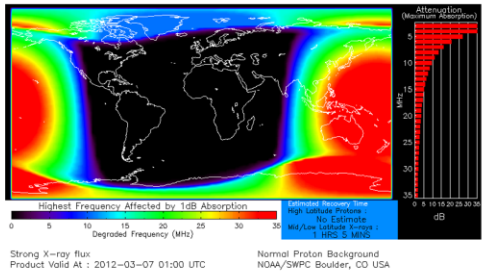

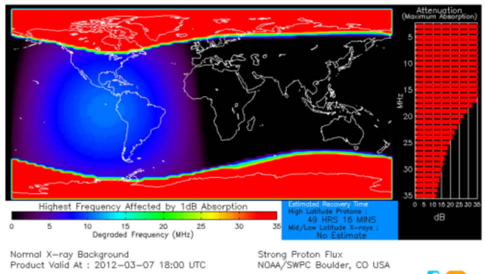

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Description of a riometer at Wiki: https://en.wikipedia.org/wiki/Riometer
A **riometer** (commonly *r*elative *i*onospheric *o*pacity meter, although originally: **R**elative **I**onospheric **O**pacity **M**eter for **E**xtra-**T**errestrial **E**missions of **R**adio noise) is an instrument used to quantify the amount of electromagnetic-wave ionospheric absorption in the atmosphere. As the name implies, a riometer measures the "opacity" of the ionosphere to radio noise emanating from cosmic origin. In the absence of any ionospheric absorption, this radio noise, averaged over a sufficiently long period of time, forms a *quiet-day curve.* Increased ionization in the ionosphere will cause absorption of radio signals (both terrestrial and extraterrestrial), and a departure from the quiet-day curve. The difference between the quiet-day curve and the riometer signal is an indicator of the amount of absorption, and is measured in decibels. Riometers are generally passive radio antenna operating in the VHF radio frequency range (~30-40 MHz). Electromagnetic radiation of that frequency is typically Galactic synchrotron radiation and is absorbed in the Earth's D region of the ionosphere.

PCA Event thresholds:
- From SWPC PCAF: ftp://ftp.swpc.noaa.gov/pub/forecasts/RSGA/README
PCAF: A 24-hour forecast of a polar cap absorption (PCA) event. PCA forecasts are color coded: PCAF Green: No active sunspot region on the Sun is likely to produce a PCA event in the 24 hours. PCAF Yellow: A sunspot region showing characteristics favorable for producing a PCA event is present on the Sun. If an energetic flare occurs in this region, the probability of a significant PCA event is very high. PCAF Red: An energetic solar event has occurred or a proton event has been observed at satellite altitudes, and there is a high probability that a significant PCA event will result within the next 24 hours. In Progress: A significant PCA event is in progress at forecast time.
- From SWPC Glossary: http://www.swpc.noaa.gov/content/space-weather-glossary#polarcapabs
polar cap absorption (PCA): An anomalous condition of the polar ionosphere where HF and VHF (3-300 MHz) radiowaves are absorbed, and LF and VLF (3-300 kHz) radiowaves are reflected at lower altitudes than normal. PCAs generally originate with major solar flares, beginning within a few hours of the event and maximizing within a day or two of onset. As measured by a riometer, the PCA event threshold is 2 dB of absorption at 30MHz for daytime and 0.5 dB at night. In practice, the absorption is inferred from the proton flux at energies greater than 10 MeV, so that PCAs and proton events are simultaneous. However, the transpolar radio paths may be disturbed for days, up to weeks, following the end of a proton event.
- From SWS: http://www.sws.bom.gov.au/HF_Systems/6/3
The icon below indicates the estimated absorption in db of a 30 MHz riometer from Casey station in Antarctica. These figures give an indication of the severity of the PCA. The background colour of the icon is red when absorption exceeds 1db and green otherwise.

Realtime view of HF is at D-RAP: http://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap

Effects from proton storms

- Polar Cap Absorption (PCA)
  - The disappearance of the HMS Acheron (1956)

From the « Amsterdam Evening Recorder » (24 February 1956)
Via https://en.wikipedia.org/wiki/HMS_Acheron_(P411)#cite_note-5
And via http://www.solarstorms.org/SRefStorms.html

Missing British Sub Feared Lost, Safe; Search Called Off
Acheron Sighted in Gale-Swept Arctic Sea by Minesweeper; Failure of Communications System Made Contact With Admiralty Impossible; Was Unreported
Since Wednesday When It Made Trial Dive

LONDON *(UP)*—The Admiralty today called off a search for the British submarine Acheron, sighted safe in gale-swept seas after being feared lost for nearly six hours. The British minesweeper Coquette radioed three hours after the Admiralty reported the Acheron overdue that she had made "visual contact" with the sub. The Coquette also reported the Acheron, carrying 65 men, said her communications system was out of order. The Acheron then proceeded to Iceland. The search started after the Acheron failed to make her routine radio report this morning. Six hours later the Admiralty said: "The Acheron has now succeeded in passing her routine check signal and as a result the search for her has been canceled.“ The 1,123-ton Acheron is a sister ship of the Affray, which sank in the English Channel in April 1951 with 75 dead. Dived 2 Days Ago The Acheron dived two days ago during arctic trials in the Denmark Strait between Iceland and Greenland and should have reported by radio at 10:05 a.m. (5:05 a.m. EST) today. This message never came.

Cont’d on next page

Effects from proton storms

- Polar Cap Absorption (PCA)
  - The disappearance of the HMS Acheron (1956)

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The Admiralty said it was possible unusual sunspot activity over the past two days might have blacked it out. Gigantic explosions on the sun have bombarded the earth with cosmic rays, interfering with communications. In Copenhagen, the Danish government's telegraph authority said no radio messages had been received from Greenland stations since yesterday "morning. "Frankly," a spokesman for the authority said, "we cannot see how a vessel could get signals through while we cannot receive a word from powerful land stations." At 11:05 am. the Admiralty flashed the "sub-miss" signal alerting all ships, planes and rescue services—military ' and civilian— to stand by for possible help. An hour later a "sub-sunk" order was flashed—signaling an immediate search with all available ships and planes. Royal Air Force planes roared off for Reykjavik, Iceland, to set up a base for search operations. U.S. Air Force units on Iceland already were standing by. Ships steamed out from Scotland and Iceland.

Some figures on the associated Ground Level Event (GLE) is in Bieber et al. (2005): Largest GLE in Half a Century: Neutron Monitor Observations of the January 20, 2005 Event
http://neutronm.bartol.udel.edu/reprints/2005bieber.pdf
The Sun occasionally emits cosmic rays of sufficient energy and intensity to increase radiation levels on the surface of Earth. From the time systematic observations by neutron monitors began in the 1950's, such "ground level enhancements" (GLEs) have occurred at a rate of about 15 per solar cycle. The largest GLE on record is the famous 1956 event [1] during which radiation levels near sea level increased by as much as 47 times in some regions.

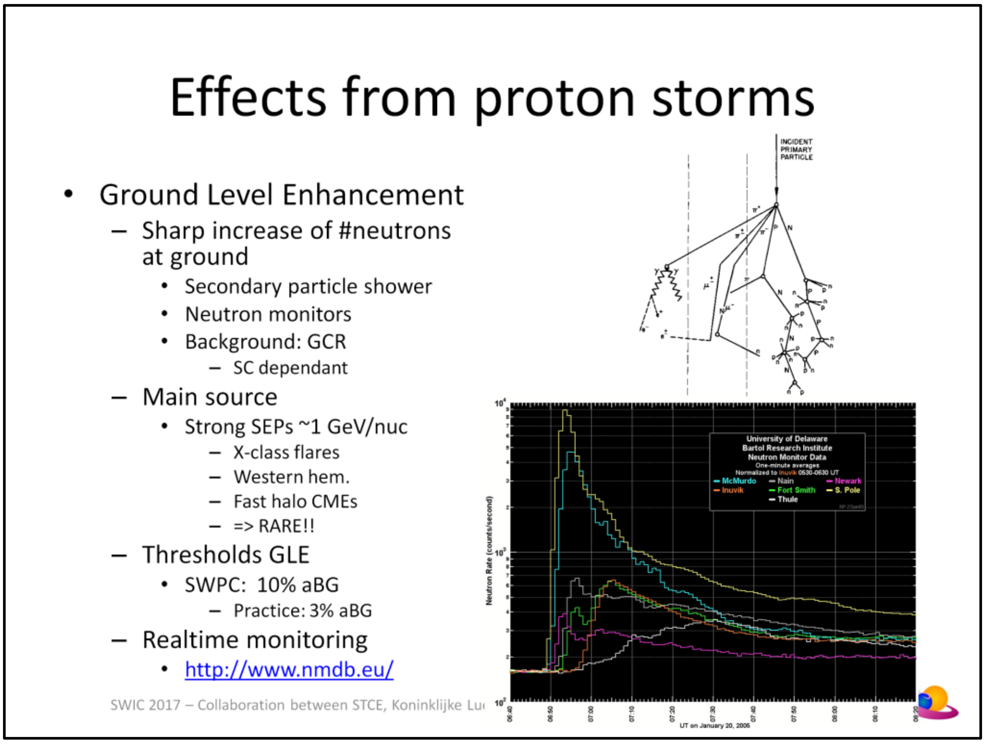
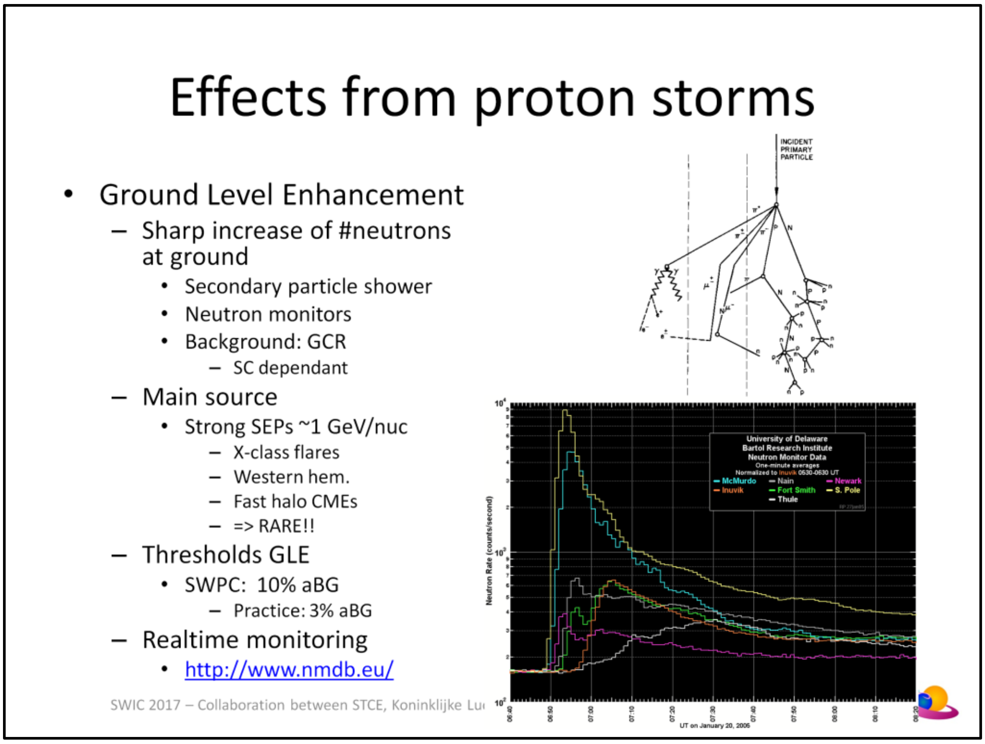


Figure taken from http://wwwgro.sr.unh.edu/neutron_monitors/shower.gif

Perrone et al. (2004): **Polar cap absorption events of November 2001 at Terra Nova Bay, Antarctica**
http://adsabs.harvard.edu/abs/2004AnGeo..22.1633P
The occurrence of SPE during minimum solar activity is very low, while in active Sun years, especially during the falling and rising phase of the solar cycle,
the SPEs may average one per month. It is well recognised that these solar particles have prompt and nearly complete access to the polar atmosphere via magnetic field lines interconnected between the interplanetary medium and the terrestrial field (van Allen et al., 1971). Consequently, they cause excess ionisation in the ionosphere, particularly concentrated in the polar cap, which, in turn, leads to an increase in the absorption of HF radio waves, termed polar cap absorption (PCA).
The ionisation occurs at various depths which depends on the incident particle energies, so that the ionisation in the D-region during PCA events is due mainly to protons with energy in the range of 1 to 100MeV that corresponds to an altitude between 30–80 km (Ranta et al., 1993; Sellers et al., 1977; Collis and Rietveld, 1990; Reid, 1974). Particles with even greater energies (>500 MeV) are recorded on the ground by a cosmic-ray detector; these events are called Ground Level Enhancement (GLE) (Davies, 1990).

Thakur et al. (2014): Ground Level Enhancement in the 2014 January 6 Solar Energetic Particle Event
http://adsabs.harvard.edu/abs/2014ApJ...790L..13T
Solar energetic particle (SEP) events, where particles accelerated to GeV energies are subsequently detected on the ground as a result of the air-shower process, are known as ground level enhancements (GLEs). With a typical detection rate of a dozen GLEs per cycle, an average of 16.3% SEP events were GLEs in cycles 19–23 (Cliver et al. 1982; Cliver 2006; Shea & Smart 2008; Mewaldt et al. 2012; Nitta et al. 2012; Gopalswamy et al. 2012a). In cycle 24, this fraction is much smaller (6.4%) with 2 GLEs out of 31 large SEP events (Gopalswamy et al. 2014). This is also much smaller than the ratio of 18% obtained when the first five years of cycle 23 are considered. GLEs are typically associated with intense flares (median soft X-ray intensity ~X3.8) and fast coronal mass ejections (CMEs; average CME speed ~2000 km s−1; see Gopalswamy et al. 2012a).



Event thresholds:

- SWPC glossary: http://www.swpc.noaa.gov/content/space-weather-glossary#groundlevelevent
ground-level event (GLE) A sharp increase in ground-level cosmic ray count to at least 10% above background, associated with solar protons of energies greater than 500 MeV. GLEs are relatively rare, occurring only a few times each solar cycle. When they occur, GLEs begin a few minutes after flare maximum and last for a few tens of minutes to hours. Intense particle fluxes at lower energies can be expected to follow this initial burst of relativistic particles. GLEs are detected by neutron monitors, e.g., the monitor at Thule, Greenland.
- Practice: List of GLE events from Gopalswamy et al. (2012): Properties of Ground Level Enhancement Events and the Associated Solar Eruptions During Solar Cycle 23 - adsabs.harvard.edu/abs/2012SSRv..171...23G (Table 1: SC23 events)

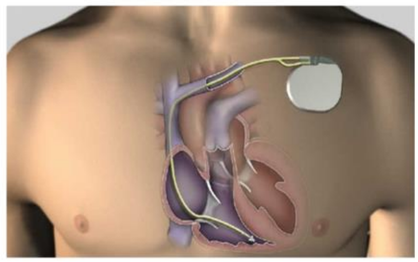
NOTE: The 6 January 2014 event is currently not considered as a genuine GLE, despite its 2.5% increase, its increase in >700 MeV protons, and the fact that other events of similar intensity (such as e.g. 17 January 2005) barely reached 3%. So GLE71 from 17 May 2012 is currently the last GLE and the only one of SC24. See the papers by Thakur (http://adsabs.harvard.edu/abs/2014ApJ...790L..13T) and Gopalswamy (http://adsabs.harvard.edu/abs/2013ApJ...765L..30G).

Between January 1976 and December 2016, there have been 6333 M-class flares and 491 X-class flares.
Only 265 proton flares were recorded, and of those there were only 45 GLEs!
Since measurements started in 1942, only 71 GLEs have been recorded, the strongest in 1956.
See list at http://neutronm.bartol.udel.edu/~pyle/GLE_List.txt and at http://natural-sciences.nwu.ac.za/neutron-monitor-data

There are some good presentations on GLE and associated radiation risk from
- the STCE Workshop at https://events.oma.be/indico/event/10/
- Bartols http://neutronm.bartol.udel.edu/

Effects from proton storms

- Ground Level Enhancements
  - Various systems
    - Computer glitches,…
    - Pacemaker and other medical devices,…
  - Effects
    - Nothing lethal
    - Errors increase with altitude
    - SC effect noted
      - More errors during SC <u>min</u> than SC <u>max</u>



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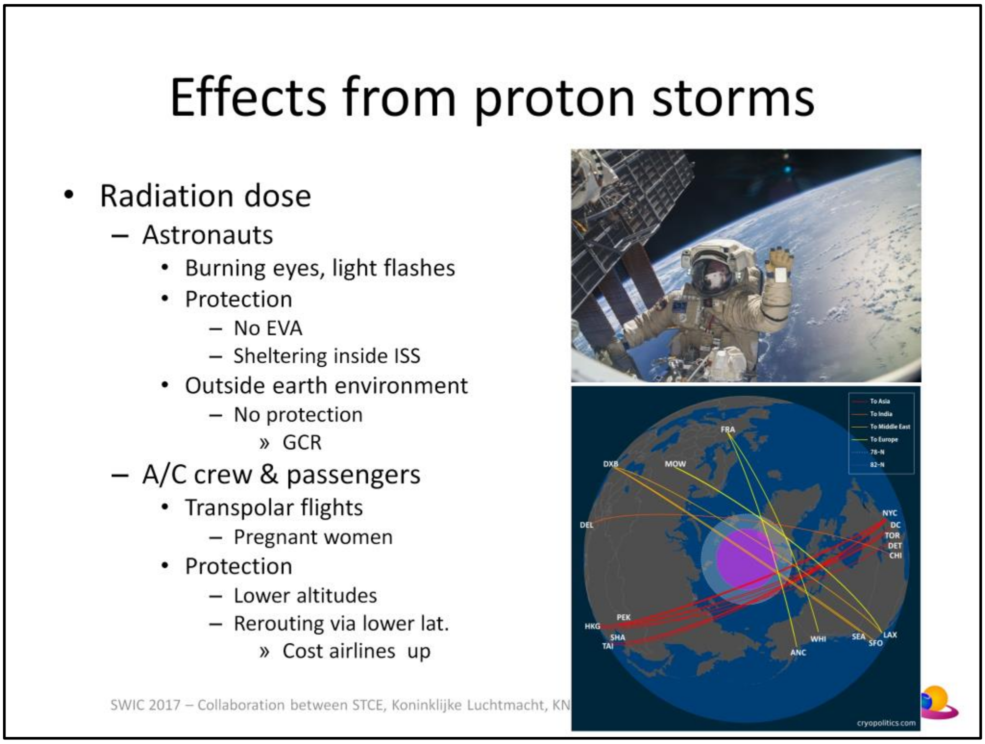
Pacemaker and other medical devices: http://www.solarstorms.org/SPacemakers.html

- Bradley et al. (1998): Single Event Upsets in Implantable Cardioverter Defibrillators
http://www.uow.edu.au/~pbradley/publications/SEUinICD.pdf
Also at http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/29/003/29003514.pdf
- Karnik et al. (2004): Characterization of Soft Errors Caused by Single Event Upsets in CMOS Processes
http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=07787359188B0540516F73B353082A93?doi=10.1.1.225.6237&rep=rep1&type=pdf
- Santarini (2005): Cosmic radiation comes to ASIC and SOC design
http://www.edn.com/design/integrated-circuit-design/4324957/Cosmic-radiation-comes-to-ASIC-and-SOC-design
- DiCello (1989): An estimate of error rates in integrated circuits at aircraft altitudes and at sea level
http://adsabs.harvard.edu/abs/1989NIMPB..40.1295D
- New Scientist (2008): Should every computer chip have a cosmic ray detector?
https://www.newscientist.com/blog/technology/2008/03/do-we-need-cosmic-ray-alerts-for.html
- Normand (2013): Single Event Upset at Ground Level
https://web.archive.org/web/20131021190327/http://pdf.yuri.se/files/art/2.pdf
- Kobayashi (2001): Evaluation of LSI Soft Errors Induced by Terrestrial Cosmic rays and Alpha Particles
http://www.rcnp.osaka-u.ac.jp/~annurep/2001/genkou/sec3/kobayashi.pdf
- Wiki: https://en.wikipedia.org/wiki/Soft_error#cite_note-cosmicRayAlert-4
- Autran and Munteanu (2015) : Soft errors: from particles to circuits
http://s1.nonlinear.ir/epublish/book/SOFT_ERRORS_FROM_PARTICALES_TO_CIRCUITS_9781466590847.pdf 5 (Table 1.4)

*** Stock market crash on 16 August 1989??
https://www.newscientist.com/article/mg12316812.400-solar-storms-halt-stock-market-as-computers-crash
http://www.edn.com/electronics-blogs/edn-moments/4394205/Solar-flare-impacts-microchips--August-16--1989
https://en.wikipedia.org/wiki/Solar_cycle_22#August_1989_geomagnetic_storm
http://www.solarstorms.org/SWChapter6.html
Coincided with a GLE.

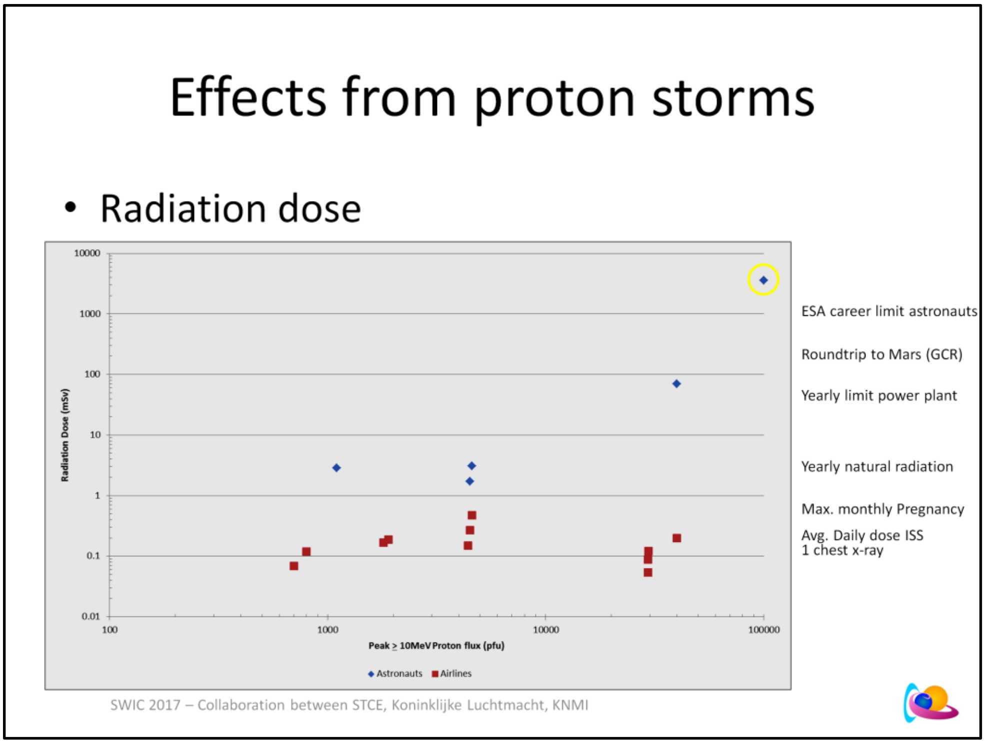


Links
Radiation dose: http://www.radiologyinfo.org/en/info.cfm?pg=safety-xray (normal yearly background: 3 mSv; chest x-ray: 0.1 mSv)
ESA career limit: http://adsabs.harvard.edu/abs/2014JSWSC...4A..20J
Flight Safety: https://flightsafety.org/asw-article/flare-ups/
ESA SSA: http://swe.ssa.esa.int/nso_air
NASA: https://srag.jsc.nasa.gov/Publications/TM104782/techmemo.htm
EPCARD: http://www.helmholtz-muenchen.de/en/epcard-portal/information/determining-radiation-exposure-of-airline-staff/index.html
Space Weather index dor radiation at aviation altitudes: http://adsabs.harvard.edu/abs/2014JSWSC...4A..13M
Pregnancy foetus: http://publicsafety.tufts.edu/ehs/radiation-safety/more-information/pregnancy-and-radiation/ (5mSv over entire pregnancy, 0.5 mSv/month)

From https://www.translatorscafe.com/unit-converter/en/radiation-absorbed-dose/18-25/milligray-millisievert/
Radiation. Absorbed Dose
The absorbed dose characterized the amount of damage done to the matter (especially living tissues) by ionizing radiation. The absorbed dose is more closely related to the amount of energy deposited.
The SI unit of absorbed dose is the **gray** (Gy), which is equal to J/kg. 1 gray represents the amount of radiation required to deposit 1 joule of energy in 1 kilogram of any kind of matter. The **sievert (Sv)** is the International System of Units (SI) derived unit of equivalent radiation dose, effective dose, and committed dose. One sievert is the amount of radiation necessary to produce the same effect on living tissue as one gray of high-penetration x-rays. Quantities that are measured in sieverts are designed to represent the biological effects of ionizing radiation.

1 mSv = 1 mGy = 100 mRem = 100 mRad
https://www.translatorscafe.com/unit-converter/en/radiation-absorbed-dose/18-25/milligray-millisievert/

There’s also an excellent discussion of the topic at https://hps.org/publicinformation/ate/q10540.html



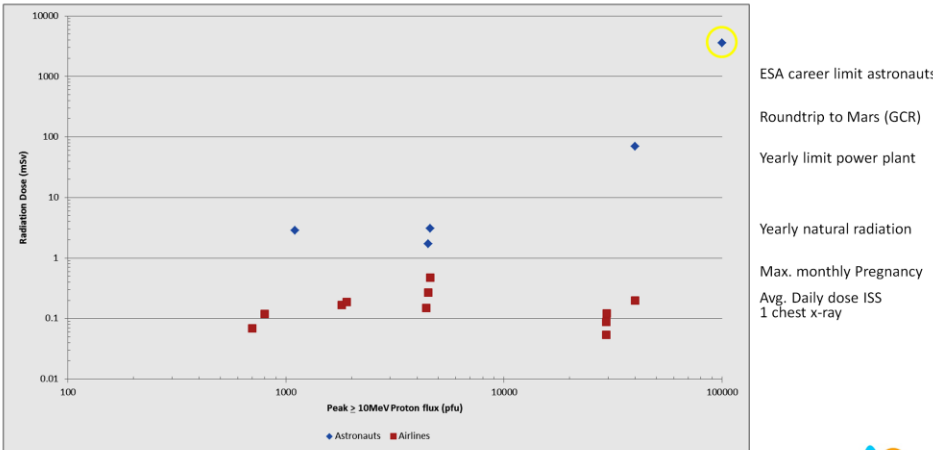
1 mSv = 1 mGy = 100 mRem = 100 mRad
https://www.translatorscafe.com/unit-converter/en/radiation-absorbed-dose/18-25/milligray-millisievert/
Also at https://hps.org/publicinformation/ate/q10540.html

Solar events
- Bütikofer et al. (2011): http://adsabs.harvard.edu/abs/2011ASTRA...7..105B
29 Sep 1989: Buenos Aires Auckland: 271 microSv; Chicago-Beijing: 156 microSv - 20 Jan 2005: Buenos Aires Auckland: 474 microSv; Chicago-Beijing: 255 microSv
Proton event: 4500pfu
- Dachev et al. (2016): http://adsabs.harvard.edu/abs/2016LSSR....9...84D
30 Sep 1989: MIR inside: 1.72 mGy (largest dose rate on MIR); 7 Mar 2012: ISS inside: 114 mGy (???) ; 22 Jun 2015: ISS outside: 2.84 mGy
Average dose inside ISS per day (SAA, CR): 0.2 mGy
Proton event: 4500pfu - 6530pfu - 1070pfu
- Guo et al. (2015): http://adsabs.harvard.edu/abs/2015ApJ...810...24G
Round trip to Mars (195 days, of which 2 days on Mars surface) during SC maximum and from GCR alone: 200 +/-100 mSv
- Matthiä et al. (2015): http://adsabs.harvard.edu/abs/2015JSWSC...5A..17M
13 Dec 2006: Seattle-Cologne - GCR: 80 microSv ; GCR+GLE: 119 microSv at FL410 (12.5km), 69 microSv at FL280 (8.5km). The reduction of 44% in dose is associated with a 5% increase in fuel consumption and a 5% (0.5h) in flight duration.
Proton event: 698pfu
- Mishev et al. (2015): http://adsabs.harvard.edu/abs/2015AdSpR..55..354M
Dose *rates* for the events of 20 Jan 2005, 13 Dec 2006 and 17 May 2012

Limits:
4500 mSv – Deadly dose (50% dies)
1000 mSv – ESA astronaut career limit
500 mSv – NASA yearly limit for astronauts
50 mSv – Yearly limit for workers at nuclear power plant
1-3 mSv – Normal yearly natural background radiation
0.5 mSv – Maximum monthly dose for pregnant women
0.2 mSv – Average daily dose ISS (from SAA+GCR)
0.1 mSv – Chest X-ray

Effects from proton storms

- Radiation dose



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Matthiä et al. (2009): http://adsabs.harvard.edu/abs/2009JGRA..114.8104M
20 Jan 2005 - X7.1 - 1860 pfu("hardest" proton event of SC23, comparable to October 1989 event) - The routes chosen are from Frankfurt to Los Angeles (FRA-LAX) as an example for a north atlantic flight and from New York to Peking (JFKPEK) as a polar flight and both flights were set to start at 0600 UTC. The calculated total effective dose for the flight FRA-LAX (JFK-PEK) is 167.7 microSv (189.4 microSv) compared to 71.1 microSv (80.0 microSv) for galactic cosmic rays only. Values are for FL360 (11km altitude).
Astronauts for same event: https://www.nasa.gov/mission_pages/stereo/news/stereo_astronauts.html
"The crew probably absorbed no more than 1 rem," said Francis Cucinotta, NASA's radiation health officer at the Johnson Space Center.

Carlowicz et al. (Storms from the Sun):
pp. 141: 1-15 August 1972: roundtrip to Moon + landing; astronauts inside module: 358 rem : Proton event: 100000pfu?
pp. 143-144: limits
pp. 145: October 1989: MIR: 7 rem ; Space Shuttle astronauts reported burning eyes + flashes even with eyes closed ; proton event : 40000 pfu ("hard" event)
pp. 149: October 1989: Concorde: 1 chest x-ray (0.1 mSv).

Dachev et al. (1992): http://adsabs.harvard.edu/abs/1992AdSpR..12..321D
29 Sep 1989 - X9 - 4500 pfu - MIR: During the SPE on the 29 of September the additional dose was 310 mrad.

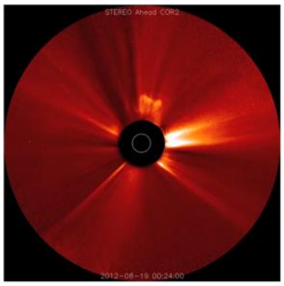
Mertens et al. (2010): http://adsabs.harvard.edu/abs/2010SpWea...8.3006M
29-30 October 2003: 11km altitude; New York (JFK) - London Heathrow (LHR): 0.054 mSv; Chicago (ORD) - Peking (PEK): 0.122 mSv - Chicago (ORD) - Stockholm (ARN): 0.088 mSv
Proton event: 29500 pfu

The spread in the event values depends on the hardness of the solar event, the altitude, for astronauts: inside/outside (amount of protection), the model/methodology/parameters used for the calculation,…

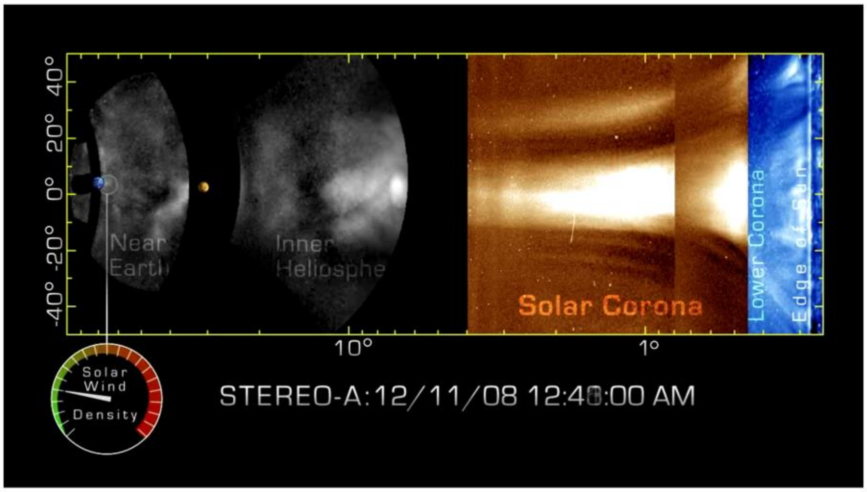
Space Weather effects (SWx effects)

- *Introduction*
- ***SWx effects from***
  - *Solar flares*
  - *Proton events*
  - ***ICMEs***
  - *Coronal holes*
- *Historical solar storms*
- *SC24 solar storms*

Coronal Mass Ejections



Effects from ICMEs



From the Sun to the Earth
https://www.nasa.gov/mission_pages/stereo/news/solarstorm-tracking.html
https://svs.gsfc.nasa.gov/10809

Effects from ICMEs

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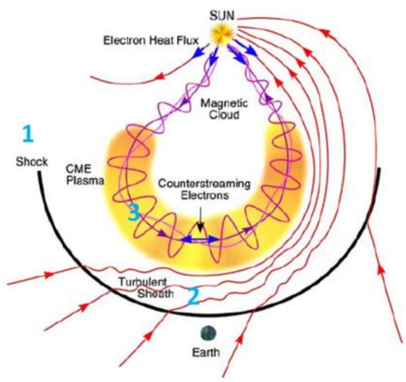
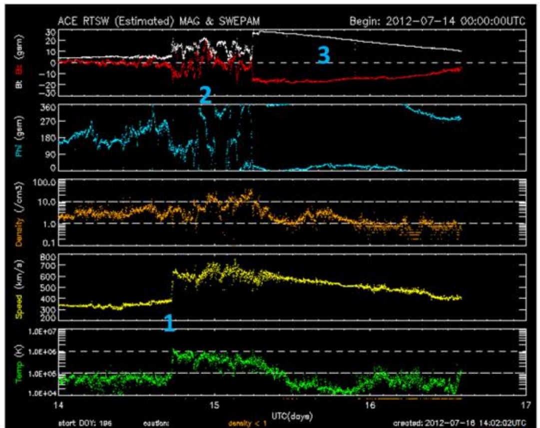
From the Sun to the Earth

Effects from ICMEs

- Solar wind features





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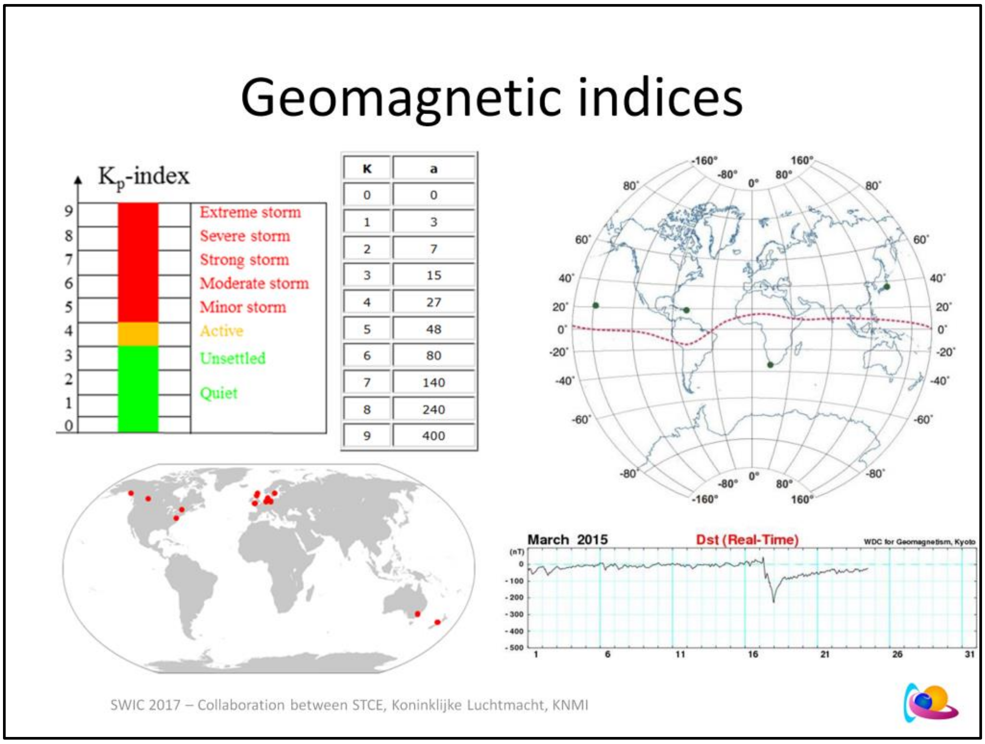
Zurbuchen et al. (2006): In-Situ Solar Wind and Magnetic Field Signatures of Interplanetary Coronal Mass Ejections
http://adsabs.harvard.edu/abs/2006SSRv..123...31Z

The solar wind example is discussed at http://www.stce.be/news/150/welcome.html



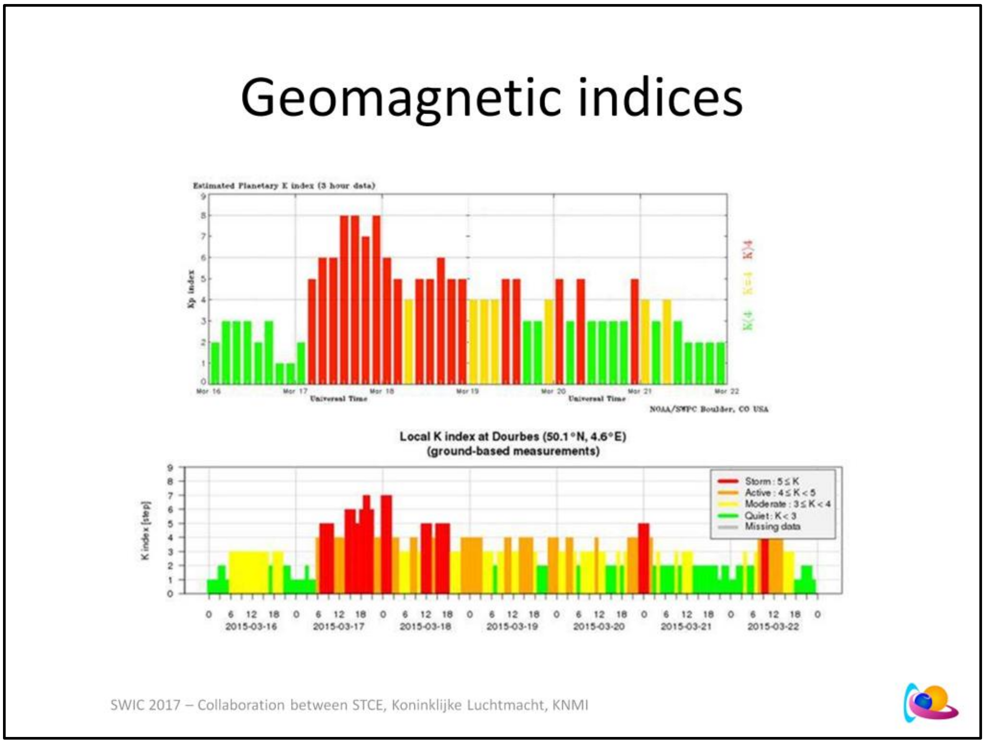
http://www.swpc.noaa.gov/sites/default/files/images/u2/TheK-index.pdf

The A-index was invented because there was a need to derive some kind of daily average level for geomagnetic activity. Because of the non-linear relationship of the K-scale to magnetometer fluctuations, it is not meaningful to take averages of a set of K indices.

http://www.stce.be/news/243/welcome.html

http://www.stce.be/news/301/welcome.html

Cander et al. (1998): Forecasting ionospheric structure during the great geomagnetic storms
http://adsabs.harvard.edu/abs/1998JGR...103..391C
The size of a geomagnetic storm is classified as moderate (−50 nT > minimum of Dst > −100 nT), intense (−100 nT > minimum Dst > −250 nT) or super-storm (minimum of Dst < −250 nT).



http://www.swpc.noaa.gov/sites/default/files/images/u2/TheK-index.pdf

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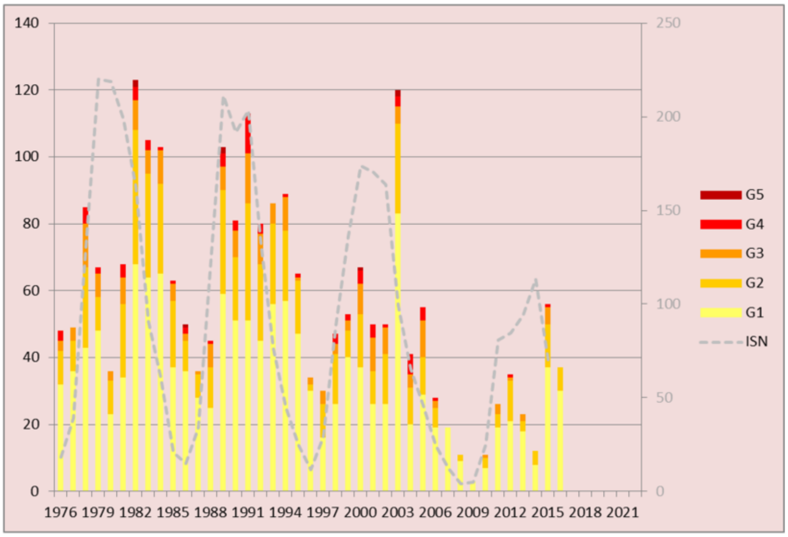
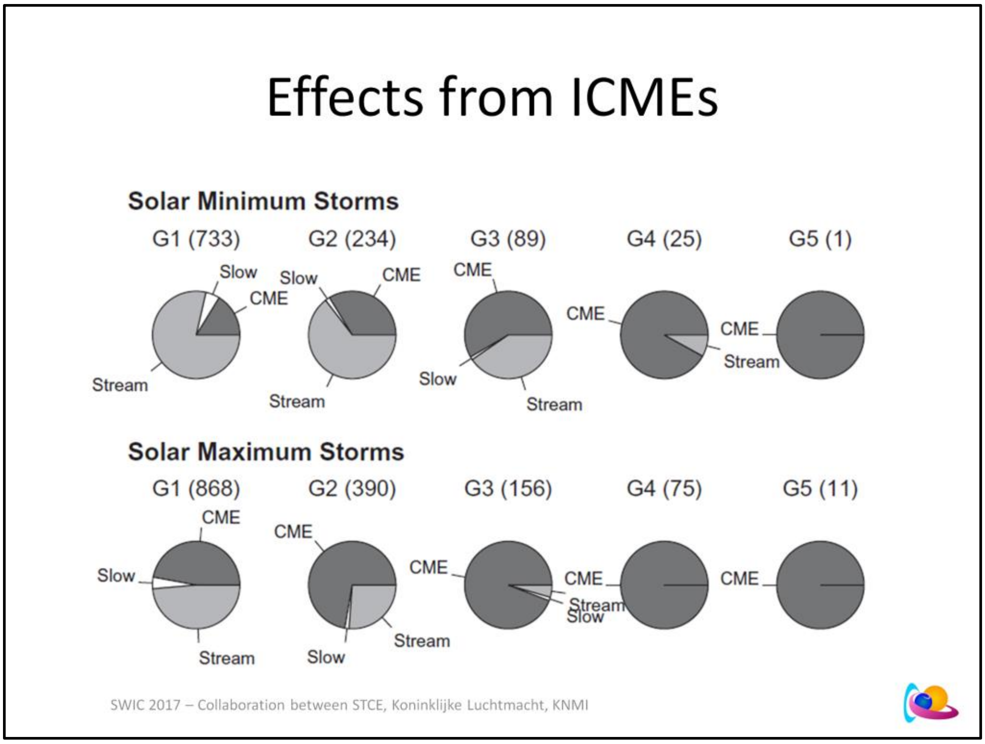
Effects from ICMEs

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

More info at
SWPC: http://www.swpc.noaa.gov/noaa-scales-explanation
http://www.swpc.noaa.gov/phenomena/geomagnetic-storms

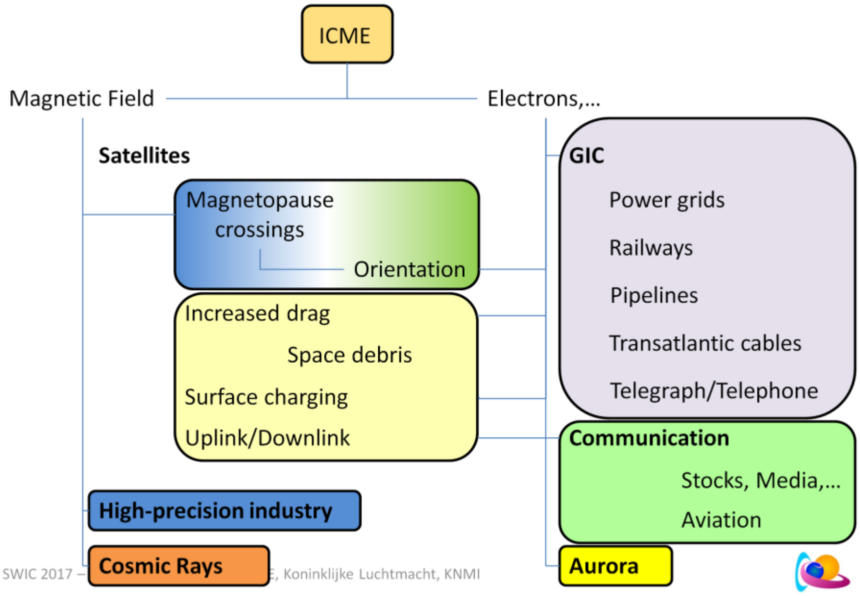
Effects from ICMEs





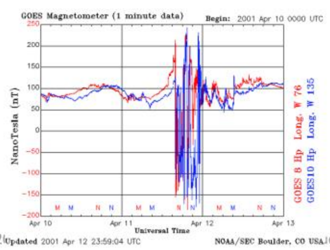
Richardson et al. (2012): Solar wind drivers of geomagnetic storms during more than four solar cycles
http://adsabs.harvard.edu/abs/2012JSWSC...2A..01R
Generally, the number of CME-associated storms (black curves in Fig. 1) follows solar activity levels, as would be expected since the ICME rate at 1 AU (Richardson & Cane 2010) and the CME rate at the Sun (Robbrecht et al. 2009; Webb & Howard 1994; Yashiro et al. 2004) increase from solar minimum to solar maximum. Furthermore, Figure 1 indicates that the maximum rate of storms driven by CME associated flows approximately follows the size of the sunspot cycle, i.e. storm rates are higher in cycles 21 and 22 than in cycles 20 and 23.
Stream-associated storms … are typically most prominent for 3–4 years during the declining phase of the Cycle The solar minimum intervals are (arbitrarily) bounded by the years in which the smoothed sunspot number fell below or rose above 40 (cf. Fig. 1), i.e., 1962 (though the analysis commenced in 1964)–1966, 1973–1977, 1984–1987, 1993–1997, and 2004–2010. Thus, these results again show the different contribution of streams and CME-associated flows at solar minimum and maximum, though CME-associated flows tend to be responsible for the most severe storms throughout the solar cycle. This conclusion is consistent with other studies, such as that of Zhang et al. (2007) which found that only ~13% of intense (Dst < -100 nT) geomagnetic storms in 1996–2005 were driven by streams, while the remainder involved CME-associated flows (ICMEs and/or upstream sheaths) (see also Echer et al. 2008).

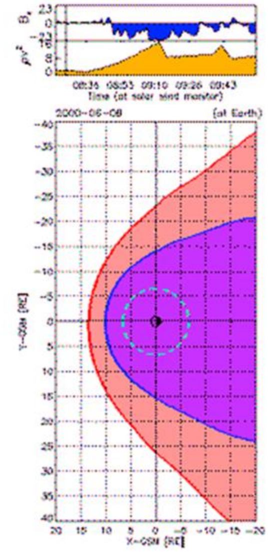
Effects from ICMEs



Effects from ICMEs

- Satellites
  - Magnetopause crossings
    - CME pushes magnetopause inside GEO
    - Satellites directly exposed to solar wind
      - Orientation problem





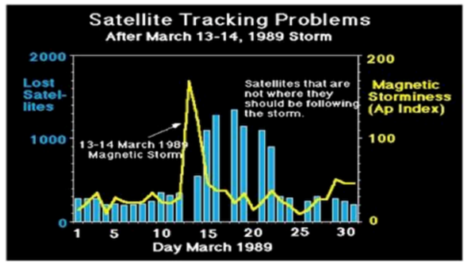
SWIC 2… …chtmacht, KNMI

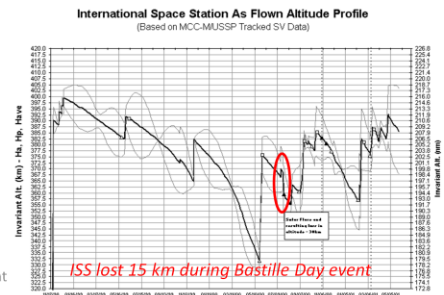
From: NOAA: Halloween Space Weather Storms of 2003
http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf
Earth's magnetopause is the boundary that separates the solar wind from the region in space dominated by Earth's magnetic field. On the line between Earth and the sun, the magnetopause is typically located about 10 Earth radii from Earth's center. On the downstream side, in the midnight region, the magnetopause forms the boundary of the elongated geomagnetic tail that extends for hundreds of Earth radii. When the solar wind dynamic pressure is very large and the interplanetary field is directed southward, conditions are ripe for moving the upstream, dayside magnetopause, from its typical location to a location closer to Earth and sometimes within geosynchronous orbit (6.6 Earth radii). At these times, when geosynchronous spacecraft on the dayside become located outside of Earth's magnetic field, they encounter highly variable magnetic fields that can be directed opposite to what is normally expected. These conditions can have undesirable effects on spacecraft that use torquer currents as part of their attitude control and momentum management. Under these conditions, spacecraft operators will sometimes turn off the spacecraft torquer currents to avoid torquing against the abnormal magnetic fields. Furthermore, the plasma environment surrounding the spacecraft is altered since the plasma density is often greater when the spacecraft crosses the magnetopause.

Animation from ESA/Cluster: http://sci.esa.int/cluster/36447-direct-observation-of-3d-magnetic-reconnection/
Top panel: z-component of the IMF (B_z), displayed in blue, and the dynamic pressure (ρv^2), displayed in orange, measured by the ACE spacecraft in the solar wind on 8 June 2000 (see text for details). Bottom panel: magnetopause position (blue line) and bow shock position (bright red line) estimated from the solar wind data as displayed in the top panel. Pink area between these two borders depicts the magnetosheath, while the purple area symbolises the magnetosphere. The dashed green circle, located at 6.6 R_E, depicts where many communication and weather satellites orbit the Earth.(Acknowledgments: S.M. Petrinec, Lockheed Martin)

Effects from ICMEs

- Satellites
  - Atmospheric drag
    - LEO
    - Sources
      - Shortterm: ICME
      - Longterm: Solar EUV radiation (solar cycle)
    - Slows down satellite
      - Burns up in atmosphere
    - Examples
      - March 1989
        - » 1000 satellites off-track
      - Premature mission end
        - » SMM, Skylab
    - Space debris
      - Cleaned up by high solar activity





Top Image from UCAR
ISS chart from Chad Hammons at http://ccar.colorado.edu/asen5050/projects/projects_2001/hammons/
It's easy to view the graphs and see that the ISS lost about 15 km altitude because of this one flare. [ed.: CME].

Drag: Bean: http://ccar.colorado.edu/asen5050/projects/projects_2007/bean/
Usually fluctuations in the Earth's magnetic field only slightly affect the atmosphere. However, perturbations in atmospheric density under extreme conditions such as geomagnetic storms are important because it causes large orbital perturbations. Geomagnetic storms are major disturbances in the earth's magnetic field driven by strong energy input from the solar wind. Large perturbations in the solar wind velocity are supplied by sources such as coronal holes and solar flares.
[3] During a coronal mass ejection (CME), the sun spews out large amounts of solar mass consisting of charged particles including solar protons at speeds exceeding 700 km/s. A coronal mass ejection directed at the earth takes about 3-4 days to make the journey to the earth. When the charged particles reach the earth, the charged particles interact with the earth's magnetosphere. The charged particles have an electric charge so the magnetic field lines around the earth influence the charged particles. The interaction of the magnetic field with the solar wind deforms the earth's magnetic field. The effect of this interaction is the compression of magnetic field lines on the dayside and stretching of field lines on the night-side to form a comet-like tail known as the magnetotail. Some of the charged particles are trapped in the magnetic field lines and eventually enter the magnetosphere. In the magnetotail, particles can move along the magnetic field lines and precipitate into the atmosphere at the earth's poles.
[4] Atmospheric density is strongly influenced by atmospheric heating from solar extreme ultraviolet (EUV) radiation and Joule heating associated with enhancements in local ionospheric and geomagnetic field currents. Solar EUV radiation makes the strongest contribution to upper atmospheric heating. Thus, satellite drag variations are mainly driven by solar influences.

Effects from ICMEs

- Satellites
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    - Slows down satellite
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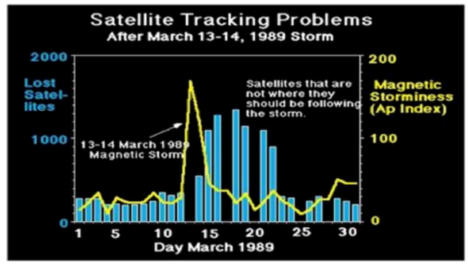
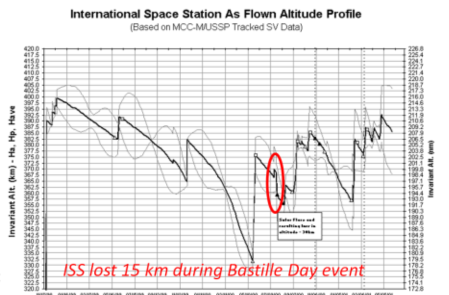


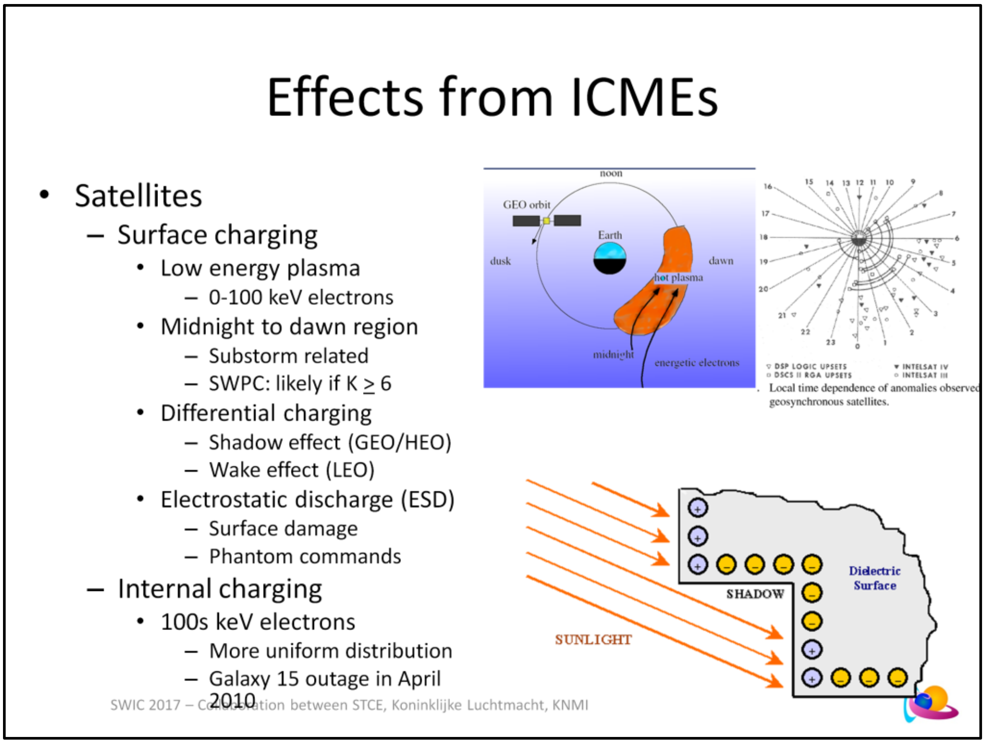


SWIC 2017 – Collaboration between STCE, Koninklijke Lucht

More info on space debris at SWPC: http://www.swpc.noaa.gov/impacts/satellite-drag
It is extremely important to keep track of spacecraft and objects flying in the space to avoid collisions with space junk and orbital debris that may be in their path. Collision avoidance has become of increasing concern due to the recent accidental hypervelocity collision of two intact spacecraft in February, 2009. The collision occurred at an altitude of 790 km, leaving pieces of debris that have been gradually separated into different orbital planes around the Earth, threatening other satellites for the next few decades. Since 1957, more than 25,000 artificial space debris have been cataloged (Figure 3), many of which have naturally decayed into the lower atmosphere. Currently, the U.S. Space Surveillance Network (SSN) tracks over 20,000 man-made objects larger than 10 cm in size, which are known as the “catalogued” population. Debris between 1 cm and 10 cm (approximately 500,000), referred to as the “lethal” population, are the most concerning as they cannot be tracked or cataloged and can cause catastrophic damage when colliding with a satellite. Objects smaller than 1 cm (approximately 135 million measuring from 1mm to 1cm, and many more smaller than 1 mm) that could disable a satellite upon impact are termed the “risk” population [3].

Skylab: Wiki: https://en.wikipedia.org/wiki/Skylab#After_departure
British mathematician Desmond King-Hele of the Royal Aircraft Establishment predicted in 1973 that Skylab would de-orbit and crash to earth in 1979, sooner than NASA's forecast, because of increased solar activity.[162] Greater-than-expected solar activity[165] heated the outer layers of Earth's atmosphere and increased drag on Skylab. By late 1977, NORAD also forecast a reentry in mid-1979;[161] a National Oceanic and Atmospheric Administration (NOAA) scientist criticized NASA for using an inaccurate model for the second most-intense sunspot cycle in a century, and for ignoring NOAA predictions published in 1976. Re-entry on 11 July 1979.

Also from SWPC: http://legacy-www.swpc.noaa.gov/info/Satellites.html
Spacecraft in LEO experience periods of increased drag that causes them to slow, lose altitude and finally reenter the atmosphere. Short-term drag effects are generally felt by spacecraft <1,000 km altitude. Drag increase is well correlated with solar Ultraviolet (UV) output and additional atmospheric heating that occurs during geomagnetic storms. Solar UV flux varies in concert with the 11-year solar cycle and to a lesser degree with the 27-day solar rotation period. Geomagnetic storms are sporadic, but most major storms occur during solar maximum years.
Most drag models use radio flux at 10.7 cm wavelength as a proxy for solar UV flux. (Before long, the GOES spacecraft will have continuous UV monitoring) Kp is the index commonly used as a surrogate for short-term atmospheric heating due to geomagnetic storms. In general, 10.7 cm flux >250 solar flux units and Kp>=6 result in detectably increased drag on LEO spacecraft. Very high UV/10.7 cm flux and Kp values can result in extreme short-term increases in drag. During the great geomagnetic storm of 13-14 March 1989, tracking of thousands of space objects was lost and it took North American Defense Command (NORAD) many days to reacquire them in their new, lower, faster orbits. One LEO satellite lost over 30 kilometers of altitude, and hence significant lifetime, during this storm.



Topright image
Fennell et al. (2001): Spacecraft Charging: Observations and Relationship to Satellite Anomalies
http://adsabs.harvard.edu/abs/2001ESASP.476..279F

2. Satellite Surface Charging

In the early 1970's, it became clear that many of the anomalies on geosynchronous satellites occurred in the near midnight to dawn region of the magnetosphere', as shown in Figure 1. This was reminiscent of the path that the hot substorm-injected electrons from the magnetotail take as they drift around the magnetosphere. Thus, it was thought that the anomalies might be substorm related and could be caused by satellite charging.
As we know, 10's of keV electrons do not penetrate the satellite surface materials but reside near the surface. The incident plasma and the solar UV also interact with materials to generate secondary electrons. The satellite's surface materials will take on a charge such that the net current between the surfaces and the plasma is zero under quiescent conditions. The result is that the surface voltages would not be zero. The sunlit areas are usually slightly positive and the shadowed areas are usually negative relative to the plasma at "infinity". If the surface was a conductor, the potential of the surface would be uniform and either positive or negative relative to the plasma.

More info at
Dr Holbert: http://holbert.faculty.asu.edu/eee560/spc-chrg.html (bottom image)
Valtonen (2004): http://www.srl.utu.fi/.../Effects_on_Tech/SpW_Effects_SpaceTech.ppt (topleft image)
Gubby et al. (2002): Space environment effects and satellite design
http://adsabs.harvard.edu/abs/2002JASTP..64.1723G

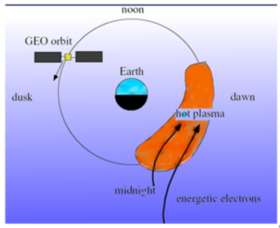
Also from SWPC: http://legacy-www.swpc.noaa.gov/info/Satellites.html

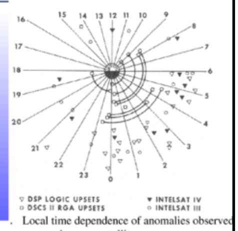
Surface Charging

Surface charging to a high voltage does not usually cause immediate problems for a spacecraft. However, electrical discharges resulting from differential charging can damage surface material and create electromagnetic interference that can result in damage to electronic devices. Variations in low energy plasma parameters around the spacecraft, along with the photoelectric effect from sunlight, cause most surface charging. Due to the low energy of the plasma, this type of charging does not penetrate directly into interior components. Surface charging can be largely mitigated through proper materials selection and grounding techniques.
Surface charging occurs predominantly during geomagnetic storms. It is usually more severe in the spacecraft local times of midnight to dawn but can occur at any time. Night to day, and day to night transitions are especially problematic during storms since the photoelectric effect is abruptly present or absent, which can trip discharges. Additionally, thruster firings can change the local plasma environment and trigger discharges.

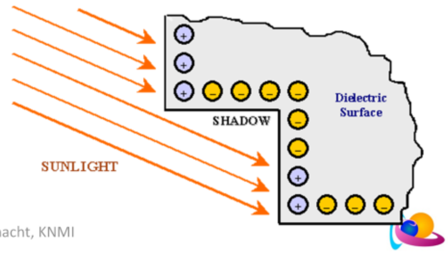
Effects from ICMEs

- Satellites
  - Surface charging
    - Low energy plasma
      - 0-100 keV electrons
    - Midnight to dawn region
      - Substorm related
      - SWPC: likely if K $\geq$ 6
    - Differential charging
      - Shadow effect (GEO/HEO)
      - Wake effect (LEO)
    - Electrostatic discharge (ESD)
      - Surface damage
      - Phantom commands
  - Internal charging
    - 100s keV electrons
      - More uniform distribution
      - Galaxy 15 outage in April 2010





Local time dependence of anomalies observed geosynchronous satellites.



The common measure for geomagnetic storms, and hence the occurrence of surface charging, is the K index. This index is a 3 hourly measure ranging from 0-9 (0=quiet, 9=severely disturbed.). It is derived from ground-based magnetometer data and is used as a surrogate for actual plasma measurements at satellite altitudes. In general, surface charging effects begin at the K=4 to K=5 level. Charging is probable at K>=6 (see Today's Space Weather). Geomagnetic substorms can be somewhat localized in space so the use of the planetary K index (Kp) may mask the severity of effect upon a specific spacecraft.

Also at STCE news item: Itchy satellites: http://www.stce.be/news/207/welcome.html

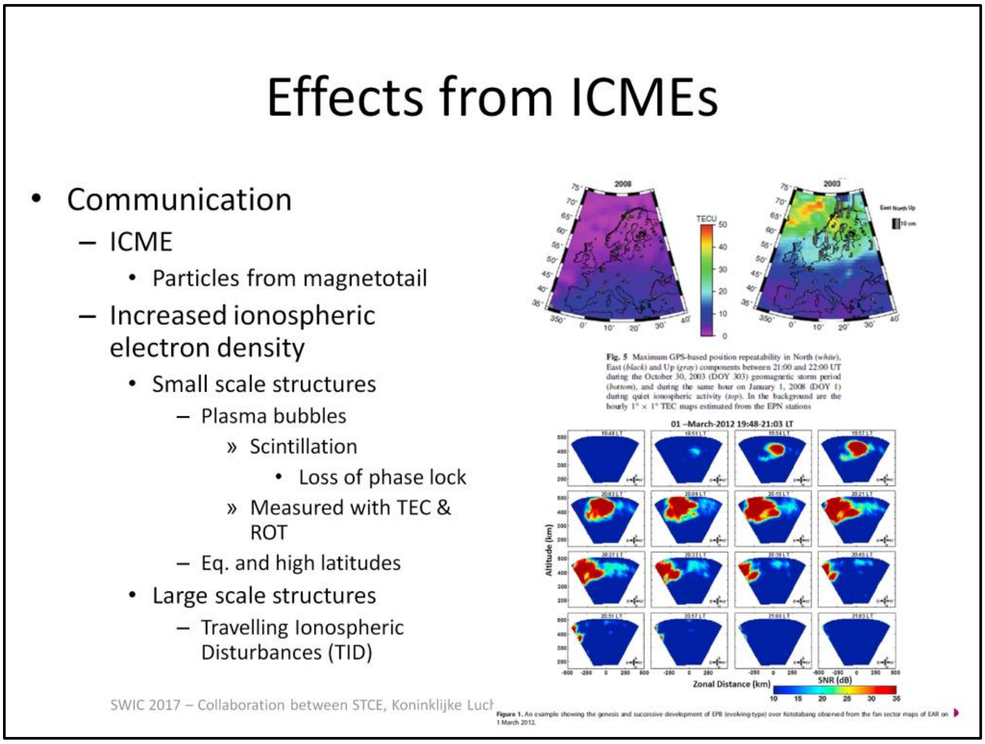
Denig et al. (2010): **Space Weather Conditions at the Time of the Galaxy 15 Spacecraft Anomaly**
https://www.ngdc.noaa.gov/stp/satellite/anomaly/2010_sctc/docs/1-2_WDenig.pdf

Internal charging: Valtonen (2004): http://www.srl.utu.fi/.../Effects_on_Tech/SpW_Effects_SpaceTech.ppt

Another example of internal charging by CME is the Telstar-401 (11 January 1997):
Odenwald: http://www.solarstorms.org/SWChapter2.html
http://sdoisgo.blogspot.be/2016/06/telstar-401-ghost-of-space-weather-past.html

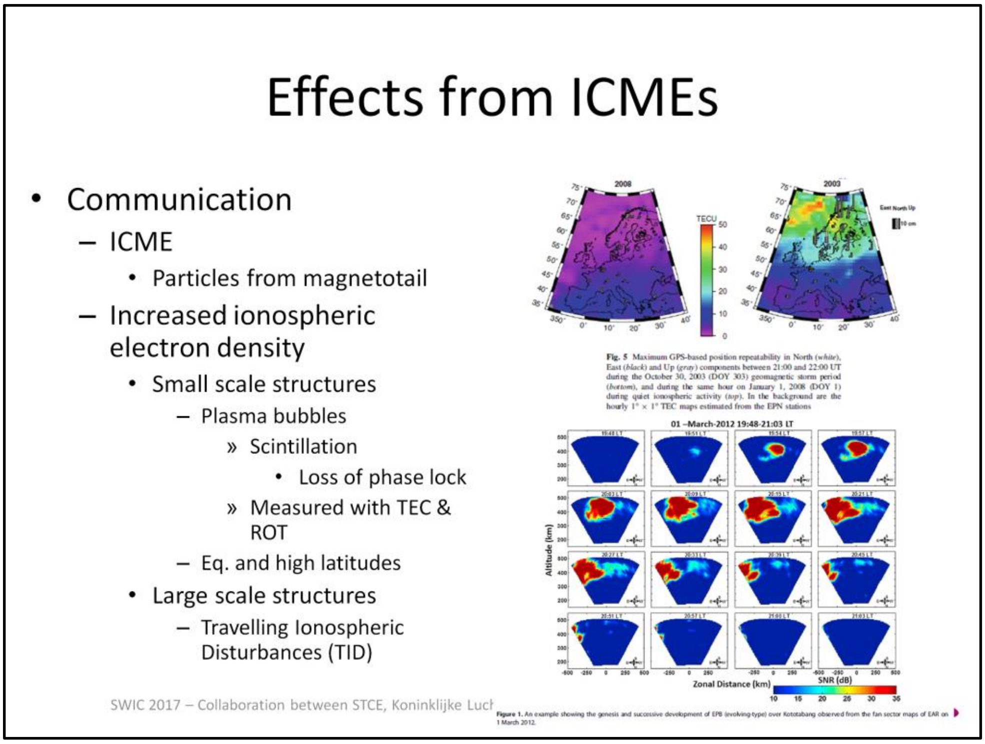
A less clear example (based more on circumstantial evidence) was the failure of the Galaxy-IV satellite, more than a week after the passage of several strong CMEs that even created a third radiation belt. The official report mentioned only technical causes, no link to the geomagnetic storms.
NASA: https://pwg.gsfc.nasa.gov/istp/outreach/events/98/
SPACECAST: http://fp7-spacecast.eu/help/bg_sa.pdf

Also at SWS: http://www.sws.bom.gov.au/Educational/1/3/2 : **Satellite Communications and Space Weather**



Bottom Picture taken from
Ajith et al. (2015): Explicit characteristics of evolutionary-type plasma bubbles observed from Equatorial Atmosphere Radar during the low to moderate solar activity years 2010-2012
http://adsabs.harvard.edu/abs/2015JGRA..120.1371A
The equatorial plasma bubbles (EPBs)/equatorial spread F (ESF) irregularities are an important topic of space weather interest because of their impact on trans-ionospheric radio communications, satellite-based navigation and augmentation systems. This local plasma-depleted structures develop at the bottom side F layer through Rayleigh-Taylor instability and rapidly grow to topside ionosphere via polarization electric fields within them. The EPBs are essentially a nighttime phenomena when the E region conductivity becomes negligible that liberates the polarization electric fields in F region to grow nonlinearly. The steep vertical gradients due to quick loss of bottom side ionization and rapid uplift of equatorial F layer via pre-reversal enhancement (PRE) of zonal electric field makes the post-sunset hours as the most preferred local time for the formation of EPBs [Kelley, 1989; Fejer et al., 1999; Tulasi Ramet al., 2006]. Once developed, these EPBs generally drift eastward with velocities ranging from 50 to 200 m/s [Aarons et al., 1980; Bhattacharyya et al., 2001; Rama Rao et al., 2005]. The seasonal and longitudinal variability of EPBs are influenced by the alignment between sunset terminator and magnetic meridian.

The top figure was taken from
Bergeot et al. (2010): **Impact of the Halloween 2003 ionospheric storm on kinematic GPS positioning in Europe**
http://rd.springer.com/article/10.1007%2Fs10291-010-0181-9
Borries et al. (2015): Ionospheric storms—A challenge for empirical forecast of the total electron content
http://adsabs.harvard.edu/abs/2015JGRA..120.3175B
Ionospheric storms have been reported since more than 80 years (cf. references in *Prölss* [2008]). In the last decades, the number of studies of ionospheric parameters during storm conditions increased significantly due to higher interest of industry and higher availability of measurements.
There exist positive storm effects (electron density enhancements compared to quiet conditions) and negative effects (electron density depletion compared to quiet conditions), often following up each other [e.g., *Baranet al.*, 2001; *Cander and Mihajlovic*, 2005; *Danilov*, 2013; *Fuller-Rowell et al.*, 1994, 1996; *Jakowski and Schlüter*, 1999]. The storm properties seem to depend not only on storm time but also on location (geomagnetic local time and latitude) and season [e.g., *Immel and Mannucci*, 2013; *Titheridge and Buonsanto*, 1988].
TEC: Total Electron Content
ROT: Rate of TEC change



The largest gradients and ionospheric disturbances in the total electron content (TEC) are usually present during positive ionospheric storms. The common view is that the main source for positive storm effects is a conservation of plasma due to uplifting. Uplifting can occur due to winds or plasma convection. In midlatitudes, equatorward winds can essentially contribute to the establishment of a positive phase of ionospheric storms. Global wind sources usually occur during day time [*Prölss*, 1995]. Convection of plasma is usually related to $E \times B$ drifts. Eastward directed electric fields produce an upward plasma drift with strongest effect in midlatitudes (at 45°N/S).

Ionospheric storms usually come along with geomagnetic storms, both influencing each other. The energy transfer mechanism between the IMF and the Earth's magnetic field is magnetic reconnection [e.g., *Southwood et al.*, 1989; *Gonzalez et al.*, 1994]. Even though both conditions, $Bz > 0$ and $Bz < 0$, result in reconnection, southward IMF produces a much stronger coupling to the solar wind than northward IMF [*Russell*, 2007].

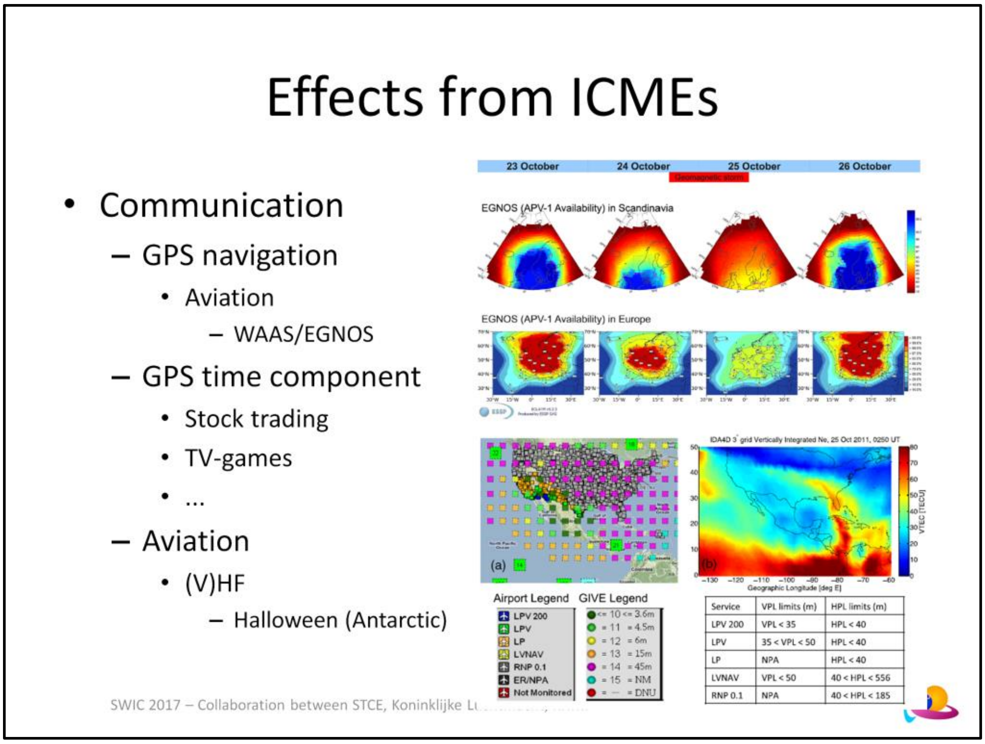
Cesaroni et al. (2015): L-band scintillations and calibrated total electron content gradients over Brazil during the last solar maximum

http://adsabs.harvard.edu/abs/2015JSWSC...5A..36C

The ionosphere is the largest contributor to the error budget for GNSS positioning (Klobuchar & Abdu 1989). Scintillation can cause degradation on GNSS measurements and, in the worst case, can lead to a signal loss of lock to the satellite, affecting the availability of the service and potentially leading to outages that could last from minutes to hours. Amplitude scintillation is traditionally monitored by means of the S4 index, which is the standard deviation of the received power normalized by its mean value, whereas phase scintillation is monitored by the r/ index, which is the standard deviation of the de-trended carrier phase. At low latitudes, the so-called ''fountain effect'', due to the interplay between E · B drift, gravity and pressure gradients, leads to an enhancement of ionization in the regions close to ±15 magnetic latitude. Such enhancements are commonly referred to as the northern and southern crest of the Equatorial Ionization Anomaly (EIA), respectively. The Rayleigh-Taylor instability, caused by the formation of the crests, allows the formation of low ionization patches, known as Ionospheric Plasma Bubbles (IPBs), when some forcing from below (e.g. gravity waves) is present. The small-scale irregularities embedded in the IPBs are the main sources for the scintillation phenomena at low latitudes (Wernik & Liu 1974). Since the 1950s, several studies (Yeh & Swenson 1959; Koster 1972; Muella et al. 2013) report that equatorial scintillations are mainly night-time events, occur in particular during the post-sunset hours and that the fluctuations of plasma density producing scintillations are located at altitudes from 200 to 400 km (F region peak altitude).

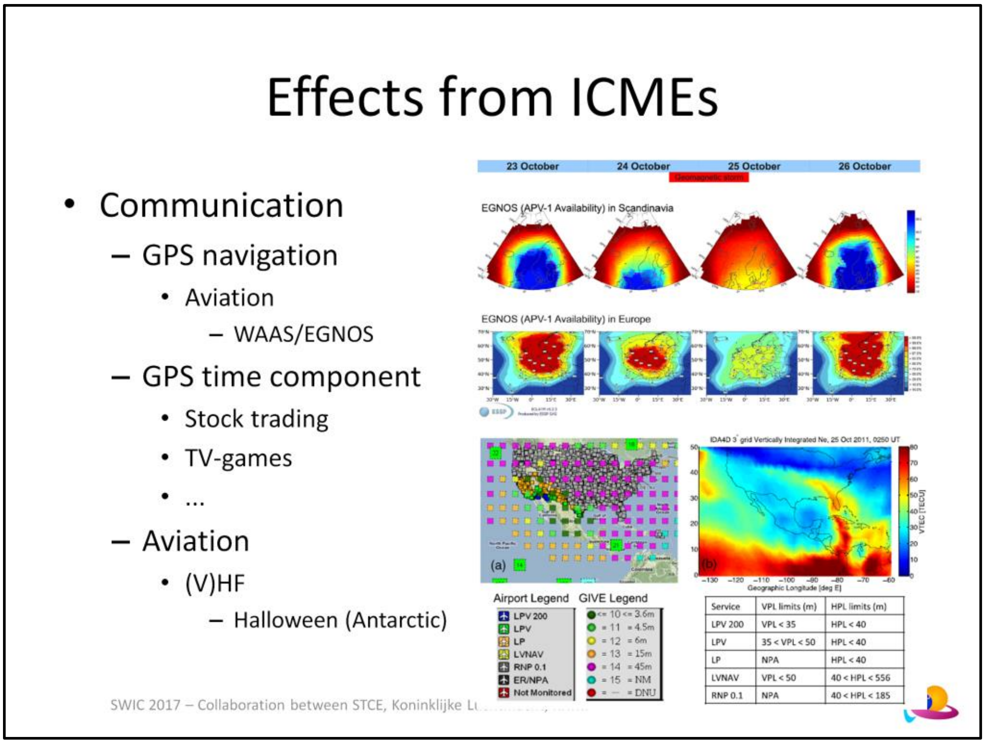
Also Basu et al. (2002): http://adsabs.harvard.edu/abs/2002JASTP..64.1745B

An example of a TID can be found in Jakowski et al. (2012): Monitoring, tracking and forecasting ionospheric perturbations using GNSS techniques - http://www.swsc-journal.org/articles/swsc/pdf/2012/01/swsc120037.pdf



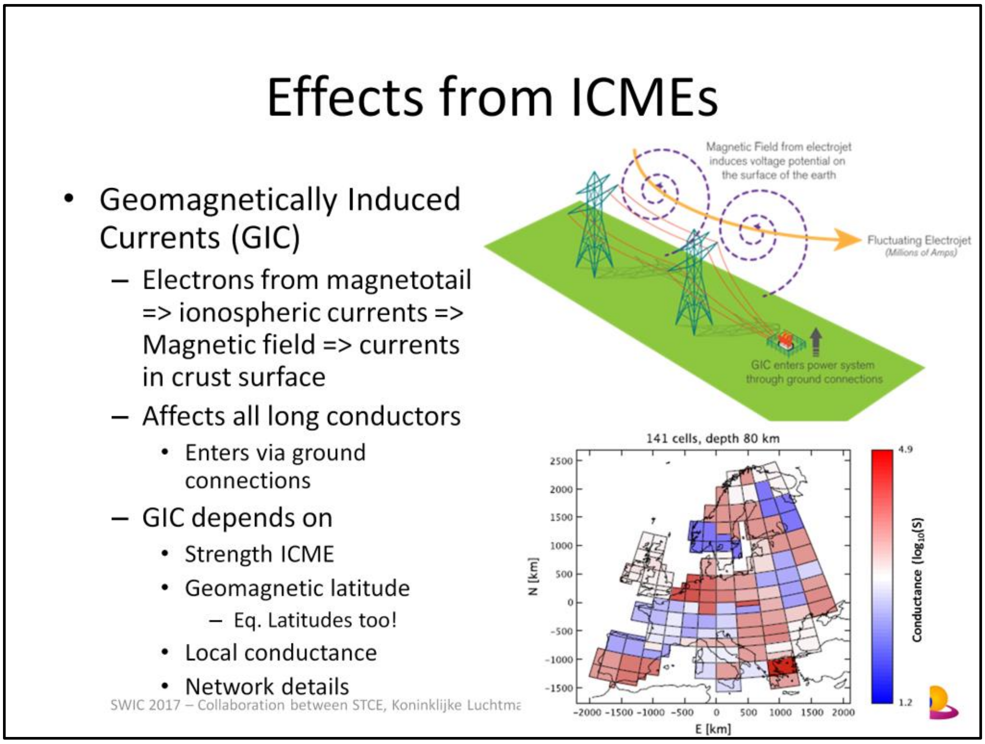
Another episode of major geomagnetic storming (Kp = 7 ; Dst = -147 nT) took place on 24-25 October 2011. The most likely source of the responsible CME seems to have been a filament eruption in the northwest solar quadrant early on 22 October. However, also the CMEs associated with the M1.3 eruption in NOAA 1319 on 21 October (peak at 13:00UT) and especially the long duration M1.3 flare in NOAA 1314 on 22 October (peak at 11:10UT) could have contributed. Space weather effects were numerous. The Earth's magnetic field got so compressed that geosynchronous satellites were briefly exposed to the solar wind. Geomagnetically induced currents were recorded in Scandinavia, and a Forbush decrease of 5.5% was recorded by neutron monitors on Earth (Oulu NM ; 5 min. data). The storm will especially be remembered for its blood red aurora, some of which were seen as far south as Oklahoma and Arizona, as well as in New Zealand and in Australia.

http://onlinelibrary.wiley.com/doi/10.1002/2013SW000982/epdf : Federal Aviation Administration’s Wide Area Augmentation System (WAAS) navigation
service in the U.S.
Solar cycle 24 has brought about increased ionospheric activity and a handful of ionospheric storms that have affected aircraft navigation services so far. None of these storms has been rated as “extreme” according to the NOAA operational definition (*Kp* = 9). WAAS vertically guided approach (LPV, LPV200) availability has been reduced on several occasions, most significantly for the 24–25 October 2011 storm. During this event the nighttime onset of geomagnetic storming seems to be correlated with a nighttime persistent, co-rotating plume of enhanced TEC extending northwestward from Florida across CONUS. TEC time-varying imaging indicates that the plasma in this plume convected northwestward, which may help to explain its shape and duration of several hours. This nighttime plume caused a loss of navigation service for several hours in CONUS. After recovering service coverage over the entire region in the local morning, dayside activity on the 25th caused a second drop in vertically guided approach coverage, but it is less severe in extent and duration.



Also European Geostationary Navigation Overlay Service EGNOS:
http://www.stce.be/esww11/contributions/public/Session7/S7-HP-03-WilkenV/VW_ESWW2014PosterV027.pdf More on EGNOS at http://www.esa.int/Our_Activities/Navigation/EGNOS/What_is_EGNOS
APV: approach procedure with vertical guidance

From: NOAA: Halloween Space Weather Storms of 2003
http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf
Antarctic
The Antarctic science groups and staff rely on a company called MacRelay to provide essential radio communications between McMurdo Station and remote sites on the Antarctic. MacRelay is also responsible for communication links with aircraft and ships supporting the United States Antarctic Program. The primary source of communication is HF radio. MacRelay experienced over 130 hours of HF communication blackout during the October – November activity. Scientific missions in the field (at camp) in Antarctica are required to 'check in' with MacRelay communications under normal circumstances via HF. If they miss their 'check in' then a rescue mission is considered. MacRelay was made aware that space weather was causing an HF blackout conditions, allowing them to implement contingency plans.



Top figure from http://www.spxtransformersolutions.com/news/FERC_GIC_2.2014.html

Bottom figure:
Viljanen et al. (2014): Geomagnetically induced currents in Europe. Modelled occurrence in a continent-wide power grid
http://adsabs.harvard.edu/abs/2014JSWSC...4A..09V
Figure 2 shows the blocks and the conductances calculated by integrating the conductivity from the surface down to 80 km. This map indicates qualitatively the expected magnitudes of the electric field. If the magnetic variation field is identical everywhere then the electric field is larger in blue areas with smaller conductivities in the top ground layers.

Carter et al. (2015): Interplanetary shocks and the resulting geomagnetically induced currents at the equator
http://adsabs.harvard.edu/abs/2015GeoRL..42.6554C
Power grid infrastructure in the equatorial region is more susceptible to space weather than previously thought. The equatorial electrojet is the primary cause of this newly recognized threat, due to its ability to amplify magnetic perturbations from interplanetary shock arrivals by several fold. These d*B/*d*t* amplifications occur on the dayside for every interplanetary shock; including those that are precursors to geomagnetic storms and those that are not. While the focus of previous research on severe geomagnetic storms has been justified (given the many reports of equipment failures in the past), the present study clearly indicates that quiet geomagnetic periods must also be considered because of the influence of the electrojet at the magnetic equator.
For equatorial countries that are relying on infrastructure not designed to cope with space weather, this finding has profound implications. Given previous equipment failures reported at midlatitudes for d*B/*d*t* levels less than 100 nT/min [*Kappenman*, 2005; *Gaunt and Coetzee*, 2007], space weather impacts are likely to be a significant factor in power stability problems at the equator. As such, future studies investigating the direct impact of interplanetary shocks on equatorial power grids are strongly encouraged.

Effects from ICMEs

- GICs
  - Power grids
    - Distortions voltage pattern
    - Transformer damage
      - South-Africa, Oct 2003
    - Grid collapse
      - Québec, March 1989
    - Longterm effects of power loss!

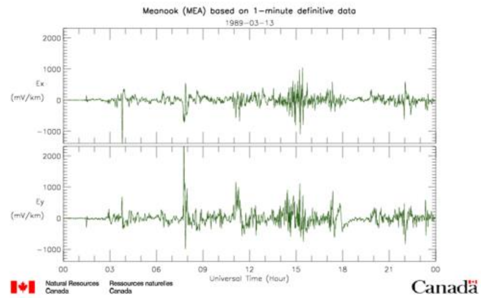
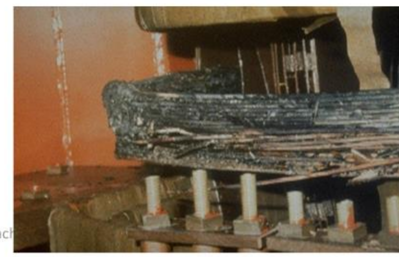


Table 3 Parameters for the GIC emergency alert model. The criterion for each alert level is shown in the second column, and the following columns show the expected extreme *dB/dt* values for RC-, AE-, and SC-type GICs

		dB/dt of GICs		
Alert level	Criterion	RC (nT/h)	AE (nT/min)	SC (nT/s)
Caution	Dst < −300 nT	100–150	2000	40–110
Warning	Dst < −600 nT	150–400	4000	40–110
Emergency	Dst < −900 nT	400–1250	6000	40–110
Transient alert	High SEP flux			40–110

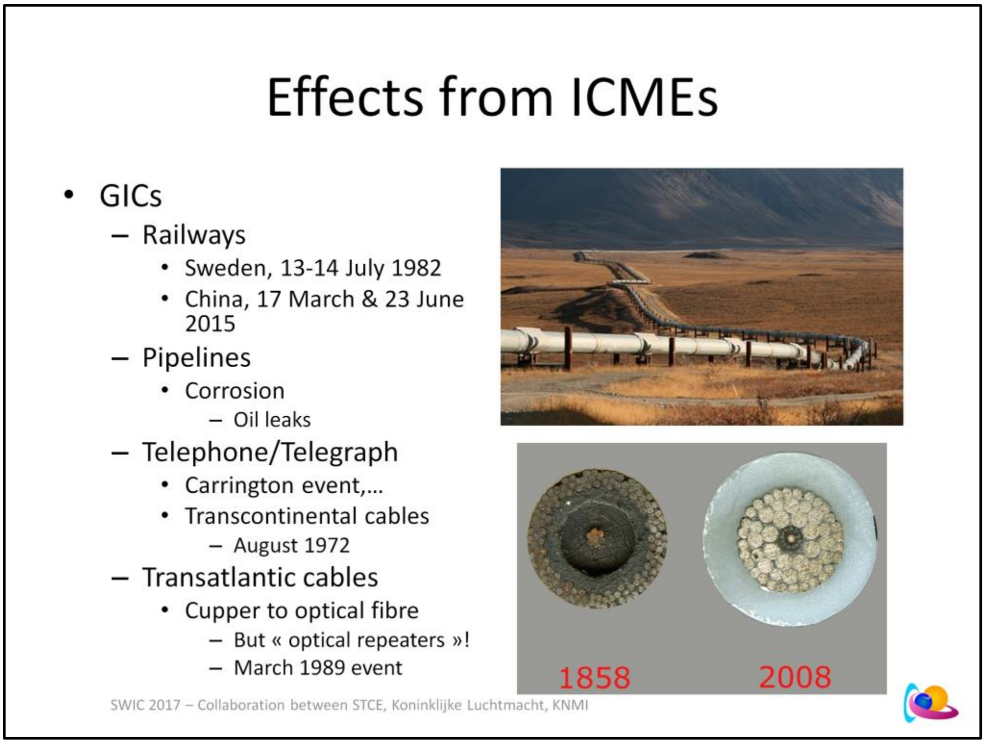
klijke Luchtmach



http://www.spaceweather.org/ISES/swxeff/5.pdf (South Africa transformers damaged)

GIC graphs available at
NR CAN: http://www.spaceweather.gc.ca/plot-tracee/geo-en.php
EURISGIC: http://eurisgic.org/

Kataoka et al. (2016): Extreme geomagnetically induced currents
http://adsabs.harvard.edu/abs/2016PEPS....3...23K

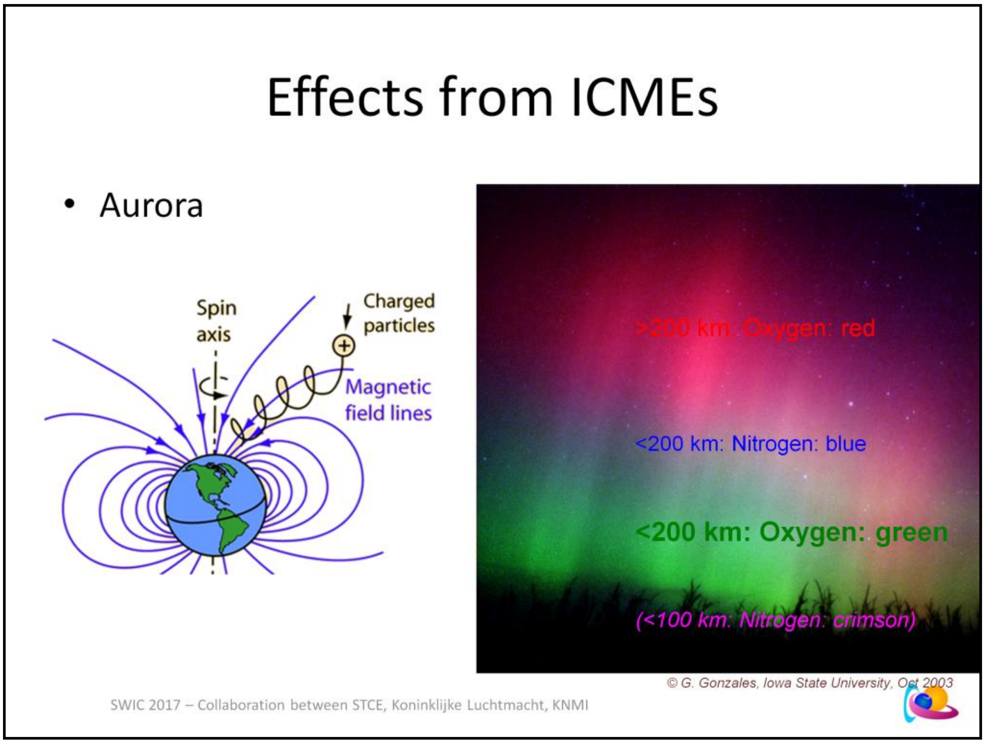


Top image from http://alyeska-pipeline.com/NewsCenter/Logos
Bottom image from http://www.submarinecablesystems.com/default.asp.pg-history

- Railways:
Liu et al. (2016): Analysis of the monitoring data of geomagnetic storm interference in the electrification system of a high-speed railway
http://adsabs.harvard.edu/abs/2016SpWea..14..754L
- Pipelines:
Hejda et al. (2005): Geomagnetically induced pipe-to-soil voltages in the Czech oil pipelines during October-November 2003
http://adsabs.harvard.edu/abs/2005AnGeo..23.3089H
- Also at http://www.windows2universe.org/space_weather/sw_in_depth/pipeline_effects.html
- Also at RNCan: http://www.spaceweather.gc.ca/tech/se-pip-en.php

Systems affected by GIC
- GIC now! (FMI): http://aurora.fmi.fi/gic_service/english/
- Transatlantic cables
Medford et al. (1981): Geomagnetic induction on a transatlantic communications cable
http://adsabs.harvard.edu/abs/1981Natur.290..392M
NRCan: http://www.spaceweather.gc.ca/tech/se-cab-en.php
- Transcontinental cables
Boteler et al. (1999): August 4, 1972 revisited: A new look at the geomagnetic disturbance that caused the L4 cable system outage - http://adsabs.harvard.edu/abs/1999GeoRL..26..577B

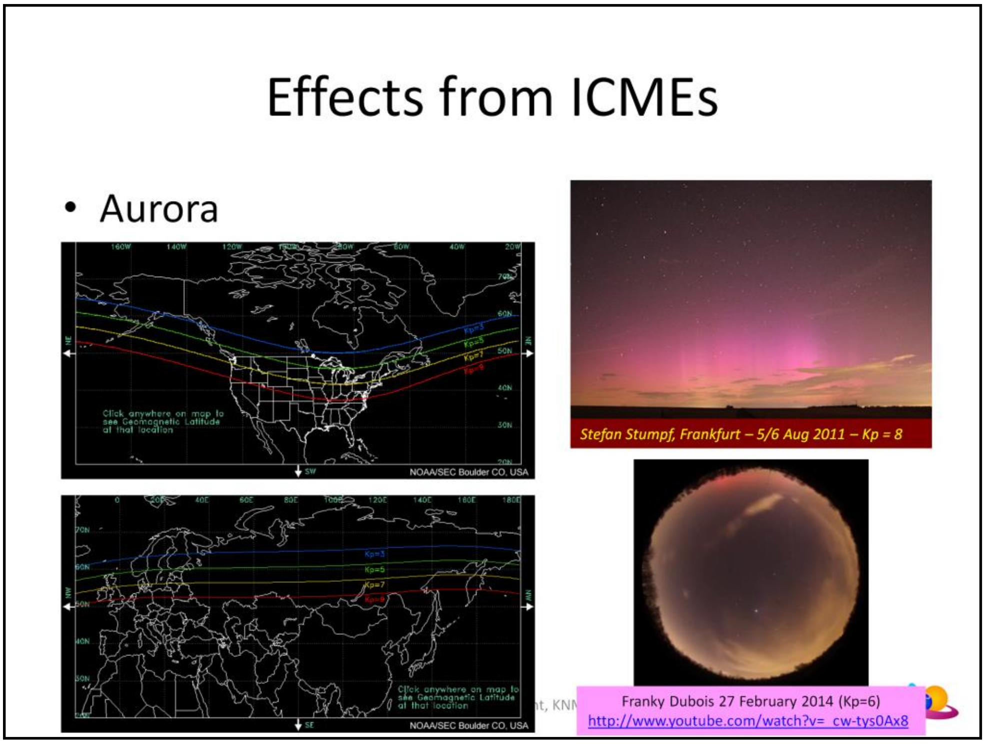
RAE (2013): Extreme space weather: impacts on engineered systems and infrastructure
http://www.raeng.org.uk/publications/reports/space-weather-full-report
However, electric power is required to drive optical repeaters distributed along the transoceanic fibres and this is supplied by long conducting wires running alongside the fibre. These wires are vulnerable to GIC effects as was demonstrated during the geomagnetic storm of March 1989. The first transatlantic optical fibre cable, TAT-8, had started operations in the previous year and experienced potential changes as large as 700 volts [*Medford et al.*, 1989]. Fortunately the power system was robust enough to cope. Similar but smaller effects were also seen during the Bastille Day storm of July 2000 [*Lanzerotti et al.*, 2001]. We are not aware of any effects occurring during the Halloween event of 2003, but that event was relatively benign in terms of GIC effects.



Abbott et al. (2016): New historical records and relationships among 14C production rates, abundance and color of low latitude auroras and sunspot abundance
http://adsabs.harvard.edu/abs/2016AdSpR..58.2181A
Auroras are generated in the ionosphere by the excitation of specific atmospheric gas species by energetic charged particles. As the gas transitions to its normal, unexcited state, it emits energy, some in the form of visible light. Auroras have a characteristic suite of emission lines in the visible spectrum. Each emission line is associated with a transition in a specific gas species. The emission line's color reflects the energy of the transition (Fig. 1B) and its intensity depends on the flux of the exciting particles and on the excitation potential of the gas species (Fig. 1A). Many visible-light auroral emissions are due to trace gasses that require different excitation energies than major components of the atmosphere, so that some important auroral emissions do not originate with the gases N2 and O2 that compose 99% of the bulk atmosphere. Atmospheric composition varies both with elevation and time. Thus, the mix of emission lines changes, depending on the mixture of gases that are being excited, the relative intensities of excitation and the depth range of the excitation within the ionosphere. The perceived color of an aurora is determined by the response of the human visual system to the mix of emission lines.
Auroral emissions are dominated by monatomic nitrogen (N1), molecular nitrogen (N2) and molecular oxygen (O2) at altitudes of 90–150 km. From altitudes of 150 to 900 km, the most important gas is monatomic oxygen (O1). Above 900 km, the most important gases are helium (He) and monatomic hydrogen (H1) (Russell, 2005b).

Sketch from Hyperphysics: http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/aurora.html

Some comments on « red aurora »:
Alaska Science Forum: http://www2.gi.alaska.edu/ScienceForum/ASF9/918.html
Spaceweather.com: http://spaceweather.com/archive.php?view=1&day=09&month=09&year=2015
Space.com: http://www.space.com/13383-spellbinding-northern-lights-display-skywatcher-photos.html



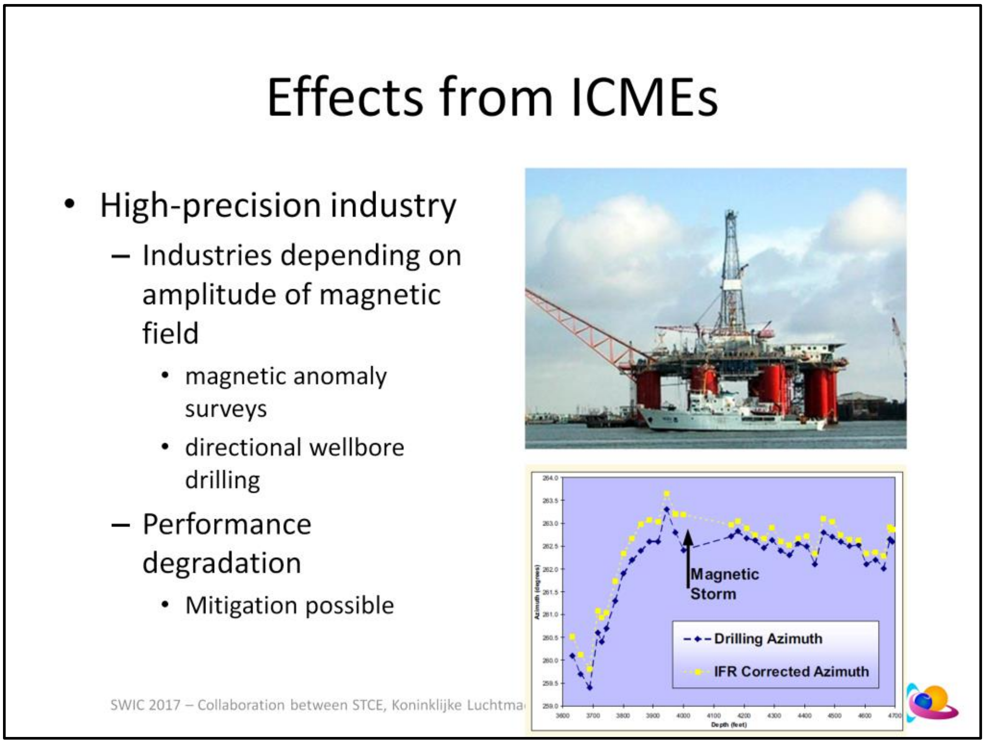
Tips on viewing the aurora:
SWPC: http://www.swpc.noaa.gov/content/tips-viewing-aurora

Another visibility chart for Western Europe: http://www.aurora-service.eu/aurora-forecast/

Visibility criteria (clear and moonless midnight, north direction without city light)

	Photographic	Visual
Belgium	Kp >= 6	Kp > 8 (9-)
Netherlands	Kp >= 5	Kp >= 7

Examples (photographic from Friesland):
12 Sep 2014 (Kp=7): http://www.stce.be/news/268/welcome.html
04 Jan 2015 (Kp=5): http://www.stce.be/news/289/welcome.html



Off-shore drilling: http://www.geomag.bgs.ac.uk/documents/estec_iifr.pdf

Precision drilling: ESA: http://swe.ssa.esa.int/nso_res

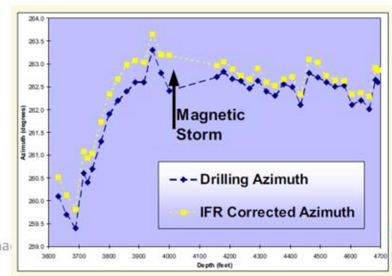
Watermann et al. (2007): The Magnetic Environment - GIC and Other Ground Effects
http://adsabs.harvard.edu/abs/2007ASSL..344..269W
The two physically oriented categories of geomagnetic effects on technological systems concern
• systems and operations which are sensitive to the magnetic field amplitude, dB. They include magnetic anomaly surveys (e.g., aeromagnetic surveys) and
directional wellbore drilling.
• systems and operations which are sensitive to the magnetic field time derivative, dB/dt. They include electric power transmission grids, oil and gas pipelines and long-distance communication cables.
The two techno-economically oriented categories of geomagnetic effects on technological systems concern
• systems which are not directly damaged by large geomagnetic perturbations but whose operational performance degrades during geomagnetically active
times. They include magnetic anomaly surveys, directional wellbore drilling and communication via long-distance cables.
• systems which may suffer equipment damage as a result of enhanced geomagnetic activity. They include electric power transmission grids and gas and oil pipelines where the damage in the former case can be immediate and in the latter cumulative and long-term.

Also at http://swe.ssa.esa.int/TECEES/spweather/workshops/esww/proc/watermann.pdf

Also at http://aurora.fmi.fi/gic_service/english/about_ground_effects.html#other_systems_affected (top image)
Magnetic surveys are used for example in oil and gas exploration. The measurements concern changes of the magnetic field, so there is a problem of separating space weather-related variations from the desired spatial variations. Scheduling surveys for periods when disturbances are forecast to be small could be a solution.

Effects from ICMEs

- High-precision industry
  - Industries depending on amplitude of magnetic field
    - magnetic anomaly surveys
    - directional wellbore drilling
  - Performance degradation
    - Mitigation possible



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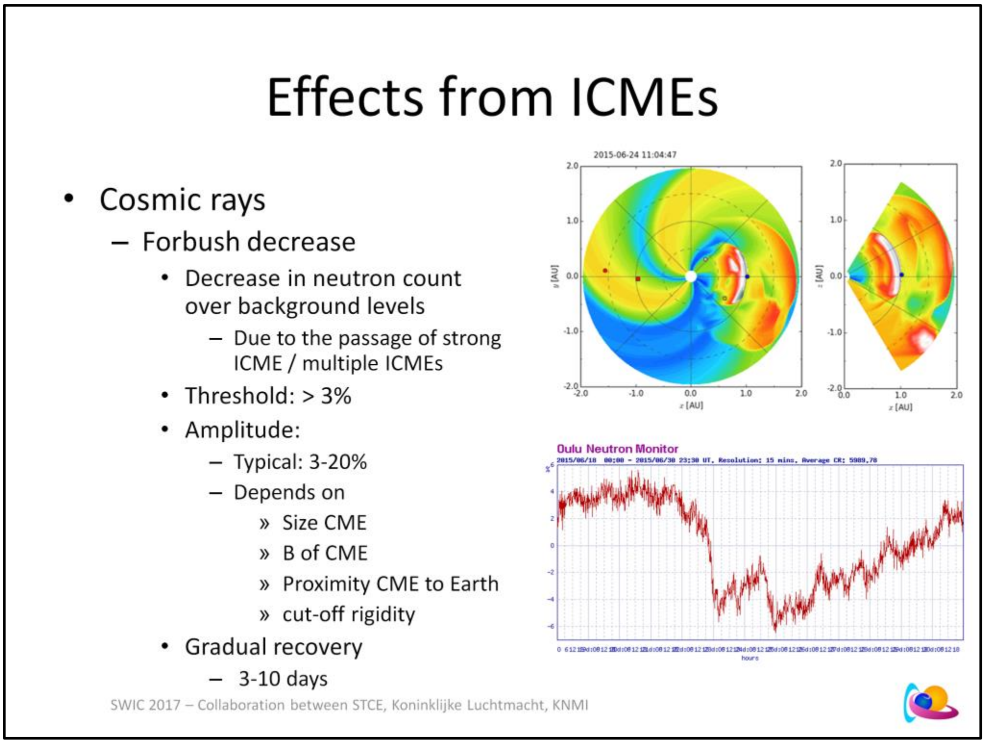
Mitigation possible:
Clark and Clarke (2001): Space weather services for the offshore drilling industry (bottom image)
http://nora.nerc.ac.uk/20528/
http://nora.nerc.ac.uk/20528/1/Clark_Clarke_ESTEC2001_SW_IIFR.pdf
The offshore oil industry use magnetic data in borehole surveying as a cheaper alternative to using gyroscopic survey tools. The technique known as
Interpolated In-Field Referencing (IIFR) has been jointly developed by BGS and Sperry-Sun Drilling Services to give accurate one-minute magnetic values at the oil well locations, enabling the technique of measurement-while-drilling (MWD) to be used.

Buchanan et al. (2013): Geomagnetic referencing: The real-time compass for directional drillers
http://www.slb.com/resources/publications/industry_articles/oilfield_review/2013/or2013aut03_geomagnetic.aspx
$\Rightarrow$ Accuracy of 0.1 to 0.01nT !!!



A discussion of the June 2015 events that lead to the Solstice storm (2nd strongest geomagnetic storm of SC24) can be found in the STCE Newsletter at
http://www.stce.be/newsletter/pdf/2015/STCEnews20150703.pdf

Topright figure: http://www.physics.helsinki.fi/vuosikertomukset/2015/research/PAPsub6.html

Other important Forbush decreases discussed in these STCE news items:
- http://www.stce.be/news/353/welcome.html
- http://www.stce.be/news/288/welcome.html
- http://www.stce.be/news/339/welcome.html

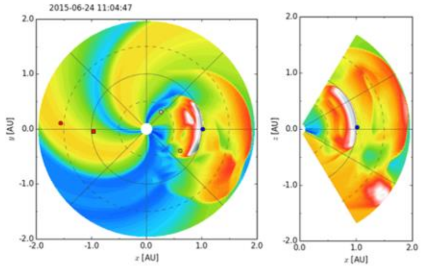
The strongest Forbush decreases in SC24 were those in March 2012 and June 2015.
http://cosmicrays.oulu.fi/webform/onlinequery.cgi?station=OULU&startday=01&startmonth=01&startyear=2008&starttime=00%3A00&endday=20&endmonth=02&endyear=2017&endtime=00%3A00&resolution=60&picture=on

Chart Forbush decrease created at http://cosmicrays.oulu.fi/

SWS: http://www.sws.bom.gov.au/Geophysical/1/4
The magnetic fields entrapped in and around coronal mass ejections exert a shielding effect on the galactic cosmic radiation (GCR) which is detected by the neutron monitors. This causes a reduction in the count rate from the monitor. The reduction is typically from about 3 to 20%. The reduction occurs typically over a timescale of several hours to a few days.
Forbush decrease events must be at least 3% for a Forbush decrease alert to be issued.
The reduction in the GCR due to a coronal mass ejection (CME) is dependent upon:
- the size of the CME
- the strength of the magnetic fields in the CME
- the proximity of the CME to the Earth

Effects from ICMEs

- Cosmic rays
  - Forbush decrease
    - Decrease in neutron count over background levels
      - Due to the passage of strong ICME / multiple ICMEs
    - Threshold: > 3%
    - Amplitude:
      - Typical: 3-20%
      - Depends on
        - » Size CME
        - » B of CME
        - » Proximity CME to Earth
        - » cut-off rigidity
    - Gradual recovery
      - 3-10 days



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Because the reduction is dependent on three factors (rather than one), it is difficult to forecast the time from a Forbush Decrease to the arrival of a coronal mass ejection at the Earth. However, previous experience in SWS is that a Forbush Decrease is a reliable indicator of a geomagnetic storm, and that warning times of up to 24 hours or more may be made. The Forbush Decrease can be used in conjunction with other indications (e.g. coronagraph imagery) to further confirm the event. Detection of a Forbush Decrease is in use at the SWS ASFC for assistance in prediction of geomagnetic storms.

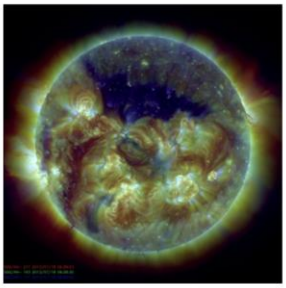
- Cane (2000): Coronal Mass Ejections and Forbush Decreases
http://adsabs.harvard.edu/abs/2000SSRv...93...55C
- Lockwood (1971): Forbush Decreases in the Cosmic Radiation
http://adsabs.harvard.edu/abs/1971SSRv...12..658L

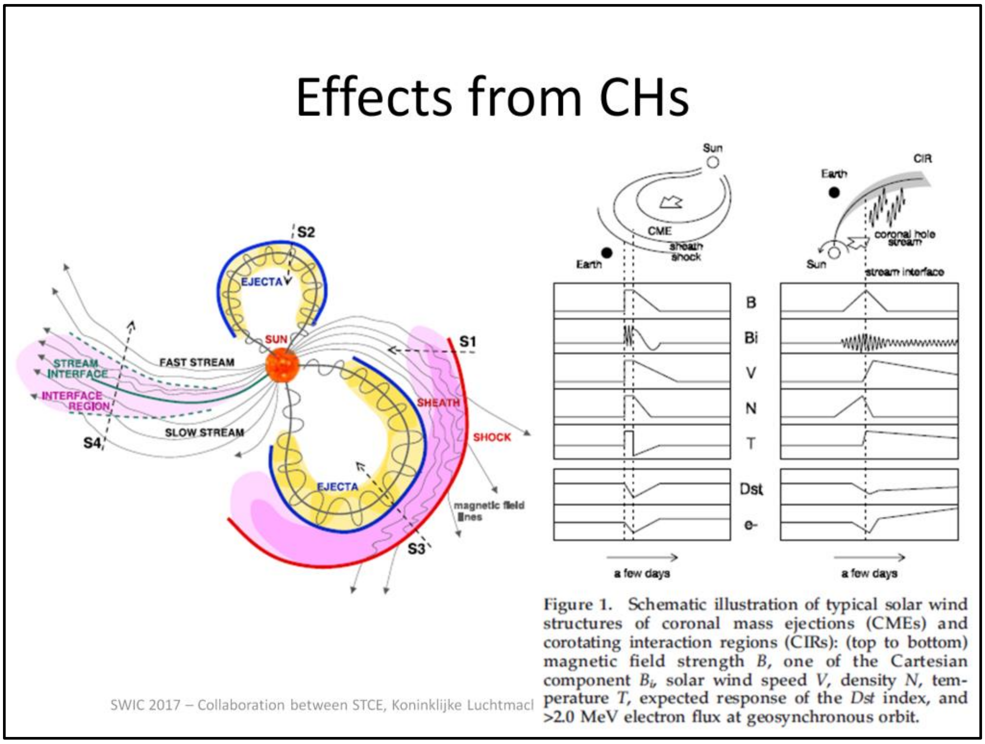
Cut-off rigidity: http://www.ph.surrey.ac.uk/satellites/main/tutorial2_1.html
It is difficult for any electrically charged particles originating from outside of the Earth's magnetosphere to enter inside it, as they tend to be deflected away via the Lorentz force. However, the tendency to be deflected is opposed to some extent by the particles' momentum. Thus, the ability of a particle to penetrate into the geomagnetic field actually depends upon a quantity called the particle's magnetic rigidity, *P.* The rigidity parameter is extremely useful in describing the motion of particles in the geomagnetic field. This is because particles injected into the field with the same rigidity will follow identical trajectories, whereas particles with the same momentum or energy, but different charges, will not. For each point in the magnetosphere there will be a minimum rigidity (called the cut-off or threshold rigidity) required to reach that point. Particles with less rigidity than the cut-off will be deflected before they reach the point, whereas those with more than the cut-off will penetrate to it.
For a particle to penetrate the Earth's field successfully, the cut-off rigidity must be low. Thus, it is easier for particles to penetrate at high magnetic latitudes L (where cos4L is minimised) than near to the magnetic equator. The equation also shows the asymmetry in cut-off rigidity with respect to arrival direction. For example, for a positive ion, it is easiest to penetrate from the West (a = 0°). Cut-off rigidity is also inversely proportional to the square of geocentric radius. Therefore, at a given latitude, penetration to lower altitudes requires a greater rigidity. In other words, at a given latitude, the particles with the highest values of rigidity will be at the lowest altitude, and the particles of lowest rigidity will be at the highest altitude.

Space Weather effects (SWx effects)

- *Introduction*
- ***SWx effects from***
  - *Solar flares*
  - *Proton events*
  - *ICMEs*
  - ***Coronal holes***
- *Historical solar storms*
- *SC24 solar storms*

Coronal Hole





Topright picture
Kataoka et al. (2006): Flux enhancement of radiation belt electrons during geomagnetic storms driven by coronal mass ejections and co-rotating interaction regions
http://adsabs.harvard.edu/abs/2006SpWea...4.9004K

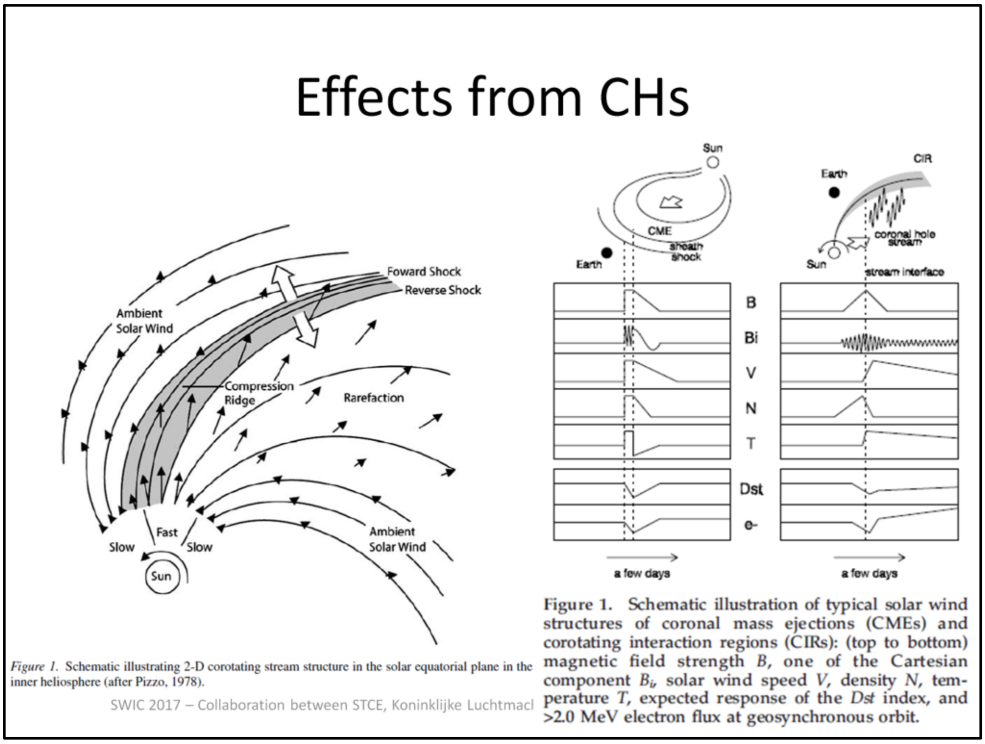
Topleft picture
Kilpua et al.: Unraveling the drivers of the storm time radiation belt response
http://adsabs.harvard.edu/abs/2015GeoRL..42.3076K

SIR/CIR
Jian et al. (2006): Properties of Stream Interactions at One AU During 1995 2004
http://adsabs.harvard.edu/abs/2006SoPh..239..337J

Jian et al. (2010): http://www-ssg.sr.unh.edu/mag/JointMeet/Jian_SIRs.pdf

More info on (C)IR and SBC in this STCE News item: SBC or CIR?
http://www.stce.be/news/269/welcome.html

More info on associated shocks in this news item: Shocking news
http://www.stce.be/news/229/welcome.html



Topright picture
Kataoka et al. (2006): Flux enhancement of radiation belt electrons during geomagnetic storms driven by coronal mass ejections and corotating interaction regions
http://adsabs.harvard.edu/abs/2006SpWea...4.9004K

Topleft picture
Kilpua et al.: Unraveling the drivers of the storm time radiation belt response
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SIR/CIR
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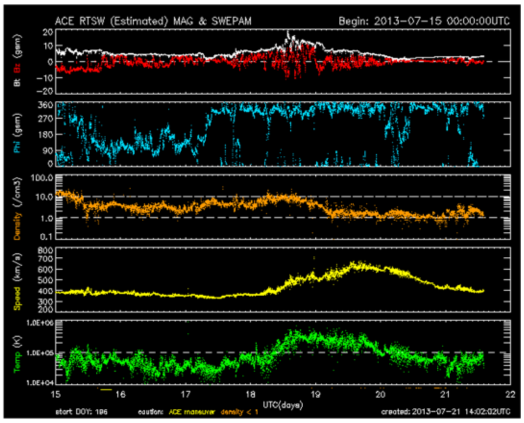
Effects from CHs



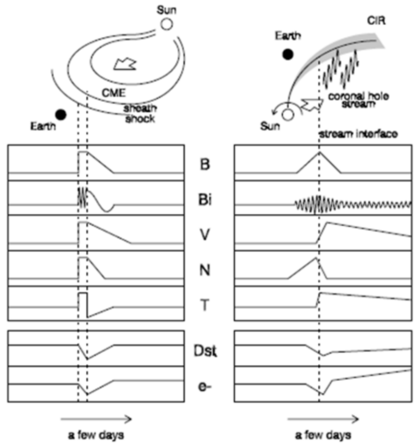


Figure 1. Schematic illustration of typical solar wind structures of coronal mass ejections (CMEs) and corotating interaction regions (CIRs): (top to bottom) magnetic field strength B, one of the Cartesian component B_i, solar wind speed V, density N, temperature T, expected response of the Dst index, and >2.0 MeV electron flux at geosynchronous orbit.

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Topright picture
Kataoka et al. (2006): Flux enhancement of radiation belt electrons during geomagnetic storms driven by coronal mass ejections and corotating interaction regions
http://adsabs.harvard.edu/abs/2006SpWea...4.9004K

Topleft: 7 day solar wind parameter chart from ACE

SIR/CIR
Jian et al. (2006): Properties of Stream Interactions at One AU During 1995 2004
http://adsabs.harvard.edu/abs/2006SoPh..239..337J

Jian et al. (2010): http://www-ssg.sr.unh.edu/mag/JointMeet/Jian_SIRs.pdf

More info on (C)IR and SBC in this STCE News item: SBC or CIR?
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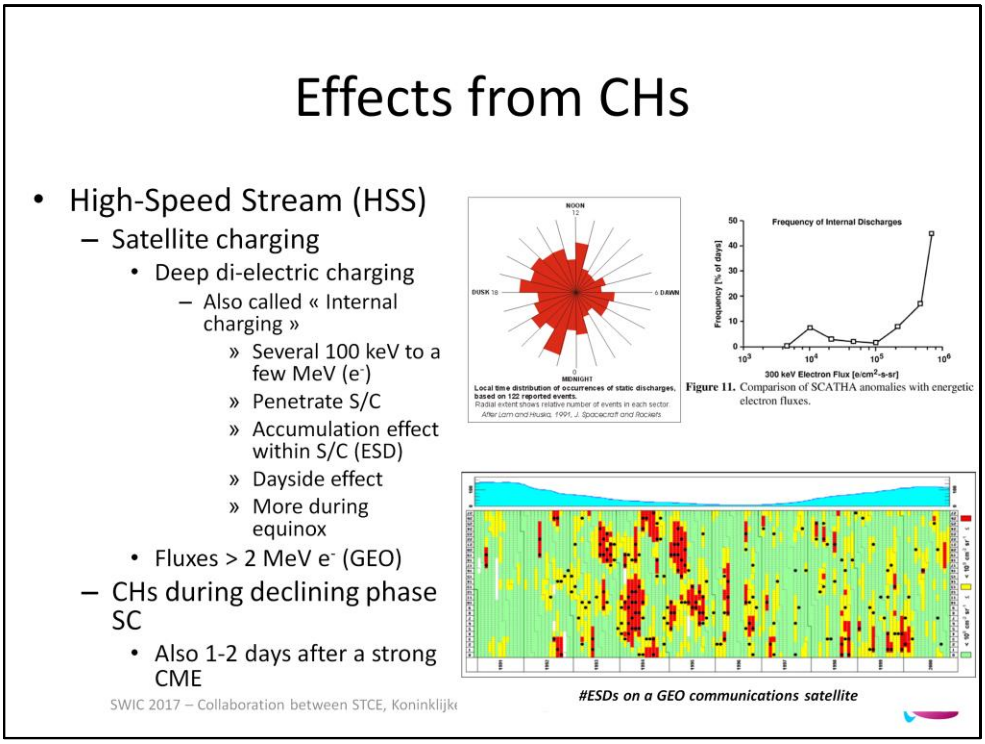


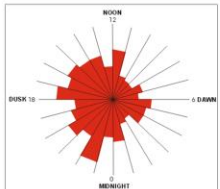
Topright figure:
Fennell et al. (2001): Spacecraft Charging: Observations and Relationship to Satellite Anomalies
http://adsabs.harvard.edu/abs/2001ESASP.476..279F

Bottomright figure:
Wrenn et al. (2002): A solar cycle of spacecraft anomalies due to internal charging
http://adsabs.harvard.edu/abs/2002AnGeo..20..953W
The maximum of the smoothed sunspot number for cycle 22 was in July 1989; the minimum in May 1996, then heralded as the start of cycle 23, which peaked in April 2000. Each day of the years 1991 through 2000 is displayed in Fig. 1 as a traffic light presentation based on the 2-day fluences of >2MeV electrons measured at geostationary GOES satellites. The days are ordered by 27.4-day Carrington solar rotations, starting with 1837 and ending with 1971; the righthand panel plots the smoothed sunspot number on a scale from 0 to 180. Black spots mark those days on which the mode switching anomalies occurred.
The outer belt electron enhancements (OBEEs) tend to last for several days but often exhibit a 27-day recurrence that reflects the persistence of coronal holes on the Sun. Their occurrence peaks not at solar maximum, but during the declining phase when high-speed streams of solar wind are more stable and long-lived. Although there is no direct correlation, the long-lived high-speed streams do occur during 1994 and 1995, approaching solar minimum, but not near solar maximum. A few bursts and associated OBEEs are obviously non-recurrent and appear to be associated with solar proton events, or perhaps coronal mass ejections. This solar cycle pattern fits well with earlier measurements made during cycle 21 (Baker et al., 1993).
Figure 3 reinforces the main message by showing the distribution of anomalies with respect to fluence, but it also explores the significance of season by plotting the switches against displacement from equinox (the line is a simple linear fit). Since coupling between the solar wind and the magnetosphere
is easier near equinox, the electron fluences are generally higher and ESD occurrence frequency can be expected to increase.

More info in this STCE Newsitem: Itchy satellites
http://sidc.be/news/207/welcome.html

Effects from CHs

- High-Speed Stream (HSS)
  - Satellite charging
    - Deep di-electric charging
      - Also called « Internal charging »
        - » Several 100 keV to a few MeV (e^-)
        - » Penetrate S/C
        - » Accumulation effect within S/C (ESD)
        - » Dayside effect
        - » More during equinox
    - Fluxes > 2 MeV e^- (GEO)
  - CHs during declining phase SC
    - Also 1-2 days after a strong CME



Local time distribution of occurrences of static discharges, based on 122 reported events.
Radial extent shows relative number of events in each sector.
After Lam and Hruska, 1991, J. Spacecraft and Rockets

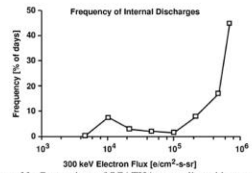
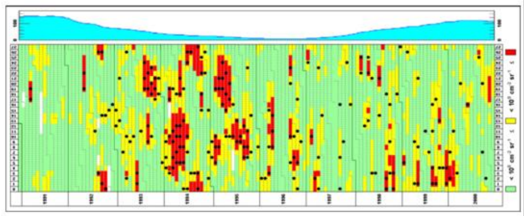


Figure 11. Comparison of SCATHA anomalies with energetic electron fluxes.



#ESDs on a GEO communications satellite

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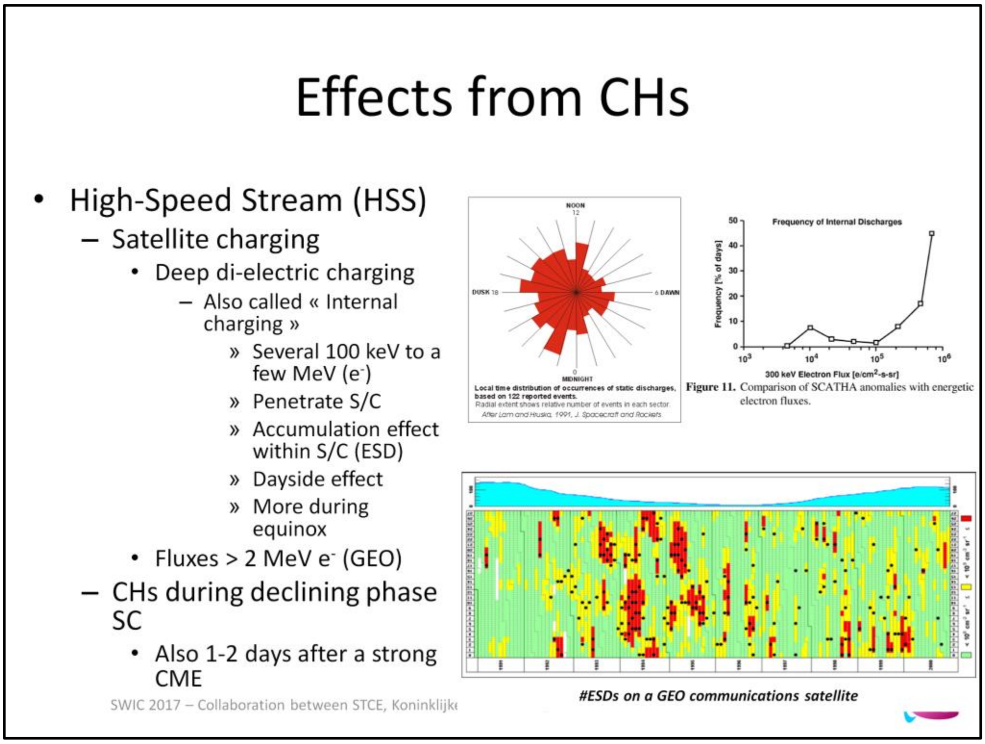
List of effects on satellites from internal charging from:
Valtonen (2004): http://www.srl.utu.fi/AuxDOC/eikka/.../SpW_Effects_SpaceTech.ppt
Internal charging effects
- Discharge producing spurious signals
  - Electromagnetic transients coupling into electronics systems
    - control signals in coaxial cables
      - unintended logic changes
      - command errors
      - phantom commands
      - spurious signals
    - loss of synchronization
    - degraded sensor performance
    - damage to sensitive components connected to discharging cable
- Physical damage
  - Localised heating
  - Breakdown of thermal coatings
  - Ejection of surface material
- Difficult to distinguish from surface charging initiated discharges
  - Environmental parameters important (correlation with high-energy electron fluxes)



Alerts:
SWPC: http://www.swpc.noaa.gov/products/goes-electron-flux
The electron flux measured by the GOES satellites indicates the intensity of the outer electron radiation belt at geostationary orbit. Measurements are made in two integral flux channels, one channel measuring all electrons with energies greater than 0.8 million electron Volts (MeV) and one channel measuring all electrons with energies greater than 2 MeV.
Electron Event ALERTS are issued when the >2 MeV electron flux exceeds 1000 particles/(cm^2 s sr). High fluxes of energetic electrons are associated with a type of spacecraft charging referred to as deep-dielectric charging. Deep-dielectric charging occurs when energetic electrons penetrate into spacecraft components and result in a buildup of charge within the material. When the accumulated charge becomes sufficiently high, a discharge or arching can occur. This discharge can cause anomalous behavior in spacecraft systems and can result is temporary or permanent loss of functionality.

Forecast at http://www.swpc.noaa.gov/products/relativistic-electron-forecast-model
NRCan: http://www.spaceweather.gc.ca/forecast-prevision/fluence/sffl-en.php
http://www.spaceweather.gc.ca/tech/se-sat-en.php
SWS: http://www.sws.bom.gov.au/Satellite/3/1

Also at Baker et al. (2004): Characterizing the Earth's outer Van Allen zone using a radiation belt content index - http://adsabs.harvard.edu/abs/2004SpWea...2.2003B
Figure 7b shows the RBC index plotted as a 27-day running average from 1992 to 2001 (upper curve). Plotted below this is the 27-day running average of the solar wind speed, VSW. It is striking that the running-averaged values of VSW were significantly greater than 500 km/s only in 1994. That obviously was the time of the highest radiation belt electron content as well.

Failure of the ANIK-1 and -2 satellites occurred during a substorm following active to minor storming activity from a number of CHs (13-19 January). Both satellites were recovered, but at a cost of about $50-70 million, and plenty of problems for cable TV, telephone, newswire and data transfer services throughout Canada.
http://www.solarstorms.org/SWChapter6.html
Leach and Alexander (1995): Failures and anomalies attributed to spacecraft charging
https://ntrs.nasa.gov/search.jsp?R=19960001539

Effects from CHs

- HSS

> 2 MeV e⁻ (GEO)	SWPC	NRCan	SWS
Flux (# / cm² s sr)	$F > 10^3$		
Fluence (# / cm² sr)	$Fl_{3d} > 10^9$	$Fl_{1d} > 5 . 10^7$	$Fl_{1d} > 10^9$
			$Fl_{1d} > 3 . 10^8$ *for 3 cons. days*

SWIC 2017 – Collab

Topright figure:
Fennell et al. (2001): Spacecraft Charging: Observations and Relationship to Satellite Anomalies
http://adsabs.harvard.edu/abs/2001ESASP.476..279F

Alerts:
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- Forecast at http://www.swpc.noaa.gov/products/relativistic-electron-forecast-model
- NRCan: http://www.spaceweather.gc.ca/forecast-prevision/fluence/sffl-en.php
- SWS: http://www.sws.bom.gov.au/Satellite/3/1

Also at
Baker et al. (2004): Characterizing the Earth's outer Van Allen zone using a radiation belt content index
http://adsabs.harvard.edu/abs/2004SpWea...2.2003B
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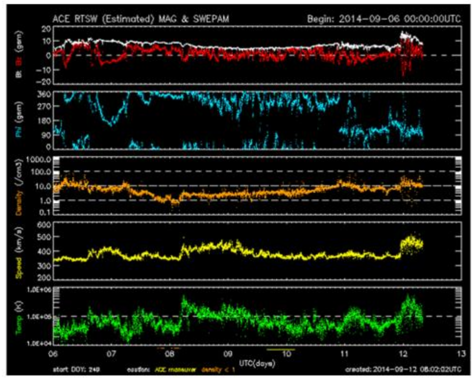
the time of the highest radiation belt electron content as well.

Effects from SBC

- Sector Boundary Crossing
  - Change IMF phi angle
    - Towards Sun <> Away Sun
    - Negative sector <> Positive sector
    - +/- 315° <> +/- 135°
  - Usually no (abrupt) change in SW speed
  - Little geomagnetic effect



SIR/CIR
Jian et al. (2006): Properties of Stream Interactions at One AU During 1995 2004
http://adsabs.harvard.edu/abs/2006SoPh..239..337J

Jian et al. (2010): http://www-ssg.sr.unh.edu/mag/JointMeet/Jian_SIRs.pdf

More info on (C)IR and SBC in this STCE News item: SBC or CIR?
http://www.stce.be/news/269/welcome.html

More info on associated shocks in this news item: Shocking news
http://www.stce.be/news/229/welcome.html

Fennell et al. (2001): Spacecraft Charging: Observations and Relationship to Satellite Anomalies
http://adsabs.harvard.edu/abs/2001ESASP.476..279F

Alerts:
SWPC: http://www.swpc.noaa.gov/products/goes-electron-flux
The electron flux measured by the GOES satellites indicates the intensity of the outer electron radiation belt at geostationary orbit. Measurements are made in two integral flux channels, one channel measuring all electrons with energies greater than 0.8 million electron Volts (MeV) and one channel measuring all electrons with energies greater than 2 MeV.
Electron Event ALERTS are issued when the >2 MeV electron flux exceeds 1000 particles/(cm^2 s sr).
High fluxes of energetic electrons are associated with a type of spacecraft charging referred to as deep-dielectric charging. Deep-dielectric charging occurs when energetic electrons penetrate into spacecraft components and result in a buildup of charge within the material. When the accumulated charge becomes sufficiently high, a discharge or arching can occur. This discharge can cause anomalous behavior in spacecraft systems and can result is temporary or permanent loss of functionality.

SWx effects - Overview

Solar source & features	Source	Flares		Particles		
	Effects	Radiation	Radio bursts	Fast Protons (SEP)	"Slow" electrons (CME)	"Fast" electrons (CH)
	Timing	Dayside	Dayside	Day&Night	Day&Night	Day&Night
	Duration	15-120 min	15-120 min	Days	Days	Days
Satellites	Technological (no comms)			Displacement damage in solar panels; Star tracking	Surface charging (~10s keV) Atmospheric drag	
	Technical failures cause Comms problems			Single Event Effects (SEE)	Internal charging (~100s keV)	Internal charging (deep di-electric) (> ~100s keV - several MeV)
	Comms (UHF)		High Frequency noise (GPS)		Dispersion & Scintillation (density variations)	Dispersion & Scintillation (density variations)
Ground Equipment	Syncronization of networks (Media,...),... Maintaining constant data flow,... (through use of GPS and satellites)		High Frequency noise (GPS)		Dispersion & Scintillation (density variations)	Dispersion & Scintillation (density variations)
	Computing facilities, medical devices,...			Little (Ground level events (GLE); only high energies e.g. > 100 MeV)		
	Transoceanic cables Telephone/Telegraph (land lines)				Geomagnetically Induced Currents (GIC)	
	Electrical power, Pipelines, Railways				Geomagnetically Induced Currents (GIC)	
	Wellbore drilling, magnetic surveys,...	Magnetic crochet			Amplitude changes in Magnetic field	
Radio Communications	Pagers, cell phones, wifi,... Satellite (nation/global) - UHF Satellite TV		High Frequency noise (GPS)	Single Event Effects (SEE)	Dispersion & Scintillation (density variations)	Dispersion & Scintillation (density variations)
	Pagers, cell phones, wifi,... Ground (local or via towers) - VHF					
	TV, FM radio stations,... (VHF)		Very High Frequency Noise	Polar Cap Absorption (PCA)	Dispersion & Scintillation (density variations)	
	AM, ground-to-air, ship-to-shore,... (HF)	Fade-Outs / Radio Black-Outs (absorption thru D-region)		Polar Cap Absorption (PCA)	Dispersion & Scintillation (density variations)	
	Aviation: Radar, WAAS/EGNOS,...		Direct interference (Radar)		Dispersion & Scintillation (density variations)	Dispersion & Scintillation (density variations)
Other	Biological: Astronauts, Aviation			Particle radiation	Forbush Decrease	

Space Weather effects (SWx effects)

- *Introduction*
- *SWx effects from*
  - *Solar flares*
  - *Proton events*
  - *ICMEs*
  - *Coronal holes*
- ***Historical solar storms***
- *SC24 solar storms*

The big solar storms of the past

Odenwald: http://www.solarstorms.org/S23rdCycle.html

Historic solar storms…

Date event	NOAA R	NOAA S	NOAA G	WLF?	Satellites / Instrum. down?	Strong GIC?	Transfo. loss?	Comms. loss?	Remarks
17 Jan 2005	3	3	3	Satellite	Some	No	No	Poles	United Airlines: 26 Polar flights detoured in 4 days!
28 Oct 2003	4	4	5	Yes	Loss of Midori-2	Yes	Malmö South-Africa	Day side	No contact with climbers Mt Everest and Trans-Atl. Sailing race Ozone layer affected Astronauts deep in ISS report « ocular shooting stars »
14 Jul 2000	3	4	5	Satellite	Loss of Astro-D	Yes	No	Poles	Ozone layer affected (1 %) ISS lost 15 km in just a few hours GPS errors double the usual
10 Mar 1989	4	3	5	Yes	Many	Yes	Québec	Poles	Tracking lost of 1300 objects! SMM burned up too soon
4 Aug 1972	3	5+	5-	Yes	-	Yes	British Columb. (CAN)	AT&T	Fastest Transit Event (FTE: 14.6 hrs!) Deadly dose for Apollo-astronauts if on the Moon
1 Sep 1859	5*	5+*	5+	Yes	-	Yes	-	Yes	First White Light Flare (WLF) Inoperable telegraph Aurora visible in Cuba & Hawaï G-storm 3* intenser than Mar 1989 Ozone layer affected (5%)

There's an excellent discussion of most of these events by S. Odenwald (NASA):
http://www.solarstorms.org/SRefStorms.html
As well as at http://www.solarstorms.org/S23rdCycle.html

Some general discussions of extreme solar activity:
- Cliver et al. (2004):The 1859 Solar-Terrestrial Disturbance And the Current Limits of Extreme Space Weather Activity
http://adsabs.harvard.edu/abs/2004SoPh..224..407C
- Cliver et al. (2013): The 1859 space weather event revisited: limits of extreme activity
http://adsabs.harvard.edu/abs/2013JSWSC...3A..31C
- Weaver et al. (2004): Halloween Space weather Storms of 2003
- Wikipedia: List of solar storms: https://en.wikipedia.org/wiki/List_of_solar_storms

*: Data from Cliver et al (2013): deduced from proxies resp. magnetic crochet en nitrogen in polar ice

Flares in X-ray (top to bottom): X3, X17, X5, X4 (X15?), X4, est. X45
Proton events: (top to bottom): 5040, 29500, 24000, 3500, 1000000 (!), 2000000 (!!)
The transformer of British Columbia exploded!
The flare of 4 Aug 1972 occurred precisely halfway between the Apollo 16 and 17 missions

Ozone layer:
http://earthobservatory.nasa.gov/Features/ProtonOzone/
http://www.newscientist.com/article/dn11456-solar-superflare-shredded-earths-ozone.html#.UneVUxCMmSo
During intense proton storms, the particles also break down N2 (molecular nitrogen), and in stead of forming again O3 (ozone), NO2 is being formed.

WLF: White Light Flare; zie http://users.telenet.be/j.janssens/WLF/Whitelightflare.html Some WLFs are seen only by satellite (TRACE, SDO).

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AT&T: a huge solar flare on August 4, 1972, knocked out long-distance telephone communication across Illinois. That event, in fact, caused AT&T to redesign its power system for transatlantic cables. See http://science.nasa.gov/science-news/science-at-nasa/2008/06may_carringtonflare/
This event followed on 3 X-class flares from 2 August that kind if « cleaned the path », hence a Fast Transit Event (FTE). Other important FTE are those from 28-29 October 2003 (19h) & 1-2 September 1859 (17h) .

Solar storms: http://www.solarstorms.org/SRefStorms.html and http://sw.astron.kharkov.ua/swimpacts.html

1300 objects: Atmospheric friction causes other headaches. During the Quebec blackout in March 1989, the U.S. Space Command had to recompute orbits for more than 1,300 objects affected by momentarily increased air resistance. Nonetheless, LEO is considered prime orbital real estate for the latest generations of communication satellite networks. See http://solar.physics.montana.edu/press/WashPost/Horizon/196l-031099-idx.html

January 2005:
https://www.easa.europa.eu/conferences/iascc/doc/Workshop%201%20Presentations/Workshop1_DAY%201/3_Murtagh_NOAA/Space%20Weather%20Impacts%20on%20Aviation%20Systems.pdf

Topleft image from https://en.wikipedia.org/wiki/Solar_storm_of_1859
Topright magnetogram taken from http://www.geomag.bgs.ac.uk/education/carrington.html

Carrington (1859): Description of a Singular Appearance seen in the Sun on September 1, 1859
http://adsabs.harvard.edu/abs/1859MNRAS..20...13C

Cliver et al. The 1859 space weather event revisited: limits of extreme activity
http://www.swsc-journal.org/articles/swsc/pdf/2013/01/swsc130015.pdf

Wiki: https://en.wikipedia.org/wiki/Solar_storm_of_1859

Some great storms in the 1920-1970s

15 May 1921 – New York Railroad System

18-19 September 1941 – Geomagnetic « Blitz »

23 February 1956 - HMS Acheron

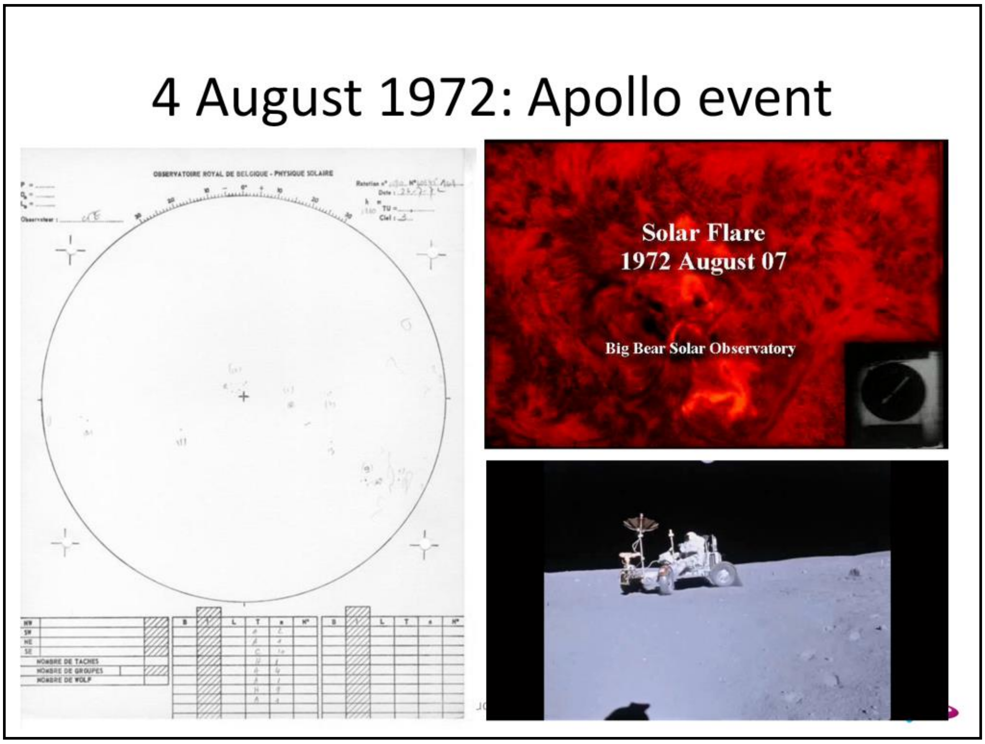
23 May 1967 – Disturbance BMEWS

May 15, 1921 - The entire signal and switching system of the New York Central Railroad below 125th street was put out of operation, followed by a fire in the control tower at 57th Street and Park Avenue. The cause of the outage was later ascribed to a ''ground current'' that had invaded the electrical system. Brewster New York, railroad officials formally assigned blame for a fire destroyed the Central New England Railroad station, to the aurora. [NYT,1921] ***This concerned the GIC effects from a CME***
https://spectregroup.wordpress.com/2010/05/12/a-carrington-event/

18-19 September 1941 - Newspapers, for example, succinctly reported that the British Royal Air Force carried out a raid on a German supply base on the Baltic Sea [*Washington Post,* 1941b] and that the Germans bombarded Leningrad [*Chicago Tribune,* 1941b], each under the lights of the aurora borealis. A German submarine torpedoed a cargo convoy and sunk the freightship HMCS Lévis. ***This concerned a CME that arrived at Earth only 20 hours after a flare was observed by RGO on 17 September. This flare caused a magnetic crochet and interfered with HF radio comms.***
https://eos.org/features/the-geomagnetic-blitz-of-september-1941

23 February 1956 – The disappearance of the HMS Acheron ***effect from PCA***

23 May 1967 - The May 1967 event was long lasting with a series of events following McMath Region 8818 across the disk of the Sun. The largest solar radio burst of the twentieth century (at specific frequencies) produced 373,000 sfu at 606 MHz. The F10.7 cm flux rose briefly to 8000 sfu. Military radio technologies were severely impacted by (1) solar radio bursts, (2) solar energetic particle deposition, and (3) general disruption of ionospheric radio and ground-to-satellite communication channels. … Such an intense, never-before-observed solar radio burst was interpreted as jamming. … With the limited data available at the time, AWS solar forecasters were able to extract sufficient information from AFCRL solar observations to convince high-level decision makers at NORAD that the Sun was a likely culprit in contaminating the BMEWs radar signals. Thus, it appears that unlike some of the human-error and miscommunication events in the 1970s [Forden, 2001], bombers did not take to the skies but were nonetheless positioned to do so.



Topleft animation from images at USET: http://www.sidc.be/uset/

Topright movie downloaded from https://www.youtube.com/watch?v=kB8InKwVIg8
Also at https://solarscience.msfc.nasa.gov/flares.shtml

Bottom right movie from NASA/Apollo 16 Lunar Rover
http://www.armaghplanet.com/blog/nasas-lunar-rover-everything-you-need-to-know.html
https://www.youtube.com/watch?v=7o3Oi9JWsyM

A discussion of this storm is at:
- NASA: https://www.nasa.gov/mission_pages/stereo/news/stereo_astronauts.html
- Odenwald: http://www.solarstorms.org/SRefStorms.html
- STCE: http://www.stce.be/news/233/welcome.html
- There were GLEs on both the 4th and 7th of August : http://natural-sciences.nwu.ac.za/neutron-monitor-data

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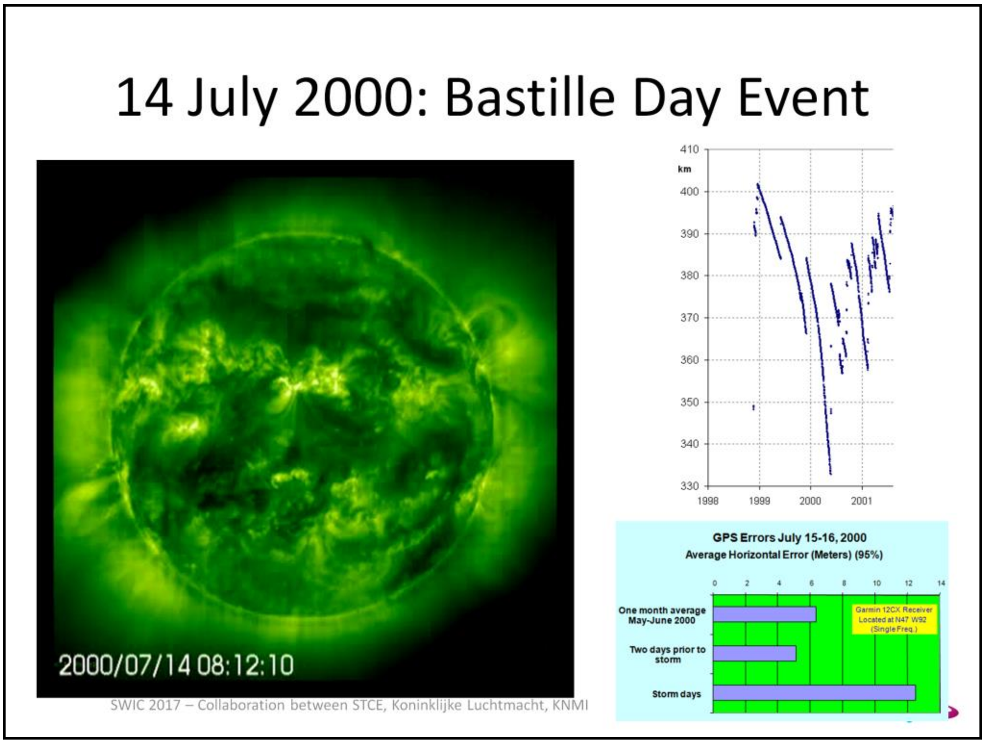
Also a transformer was destroyed: https://ics-cert.us-cert.gov/advisories/ICSA-11-084-01

Topleft animation from images at USET: http://www.sidc.be/uset/

Topright movies obtained from http://sfd.njit.edu/ (NJIT Solar Film Digitization Project)
Bottom right image from
http://www.windows2universe.org/space_weather/sw_in_depth/sw_voltage_transformer_damage.html
Image courtesy of Public Service Electric and Gas and Peter Balma.

Wiki: https://en.wikipedia.org/wiki/March_1989_geomagnetic_storm
Odenwald: https://www.nasa.gov/topics/earth/features/sun_darkness.html
Odenwald: http://www.solarstorms.org/SWChapter1.html
Space.com: http://www.space.com/24983-auroras-1989-great-solar-storm.html



Left movie from https://sohowww.nascom.nasa.gov/gallery/Movies/flares.html
Topright image from http://www.heavens-above.com/IssHeight.aspx (old)
Bottomright image from
http://www.ofcm.gov/risk/presentations/day%201/1_intro_obj/fc_welcome_intro_obj_updated.ppt
(old)

Wiki: https://en.wikipedia.org/wiki/Bastille_Day_event
Watari et al. (2001): The Bastille Day (14 July 2000) Event in Historical Large SUN EARTH Connection
Events
http://adsabs.harvard.edu/abs/2001SoPh..204..425W
http://earthobservatory.nasa.gov/Features/ProtonOzone/

http://www.spaceweather.org/ISES/swxeff/5.pdf (South Africa transformers damaged)

Plunkett: https://www.nrl.navy.mil/content_images/05FA5.pdf
Weaver et al.: HALLOWEEN SPACE WEATHER STORMS OF 2003
http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf

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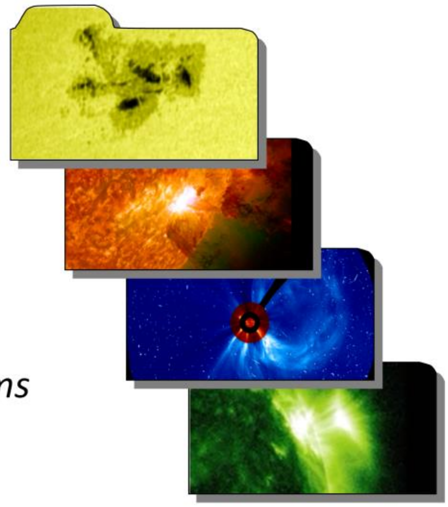
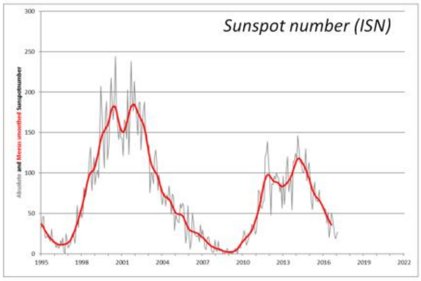
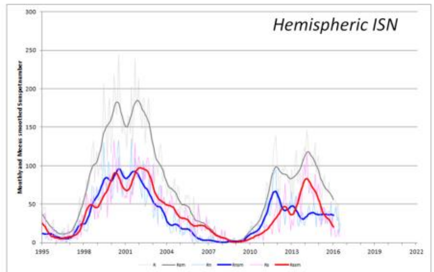
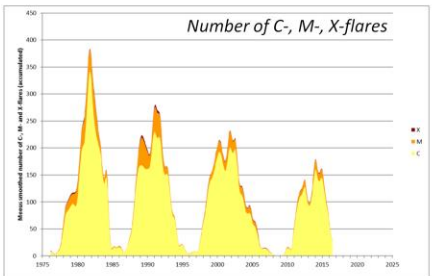


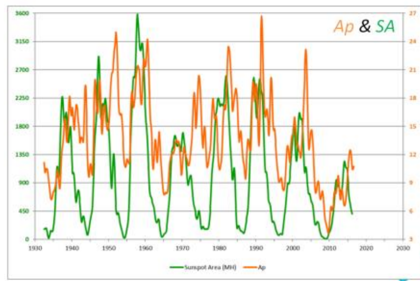
Solar Cycle 24

http://users.telenet.be/j.janssens/SC24web/SC24.html

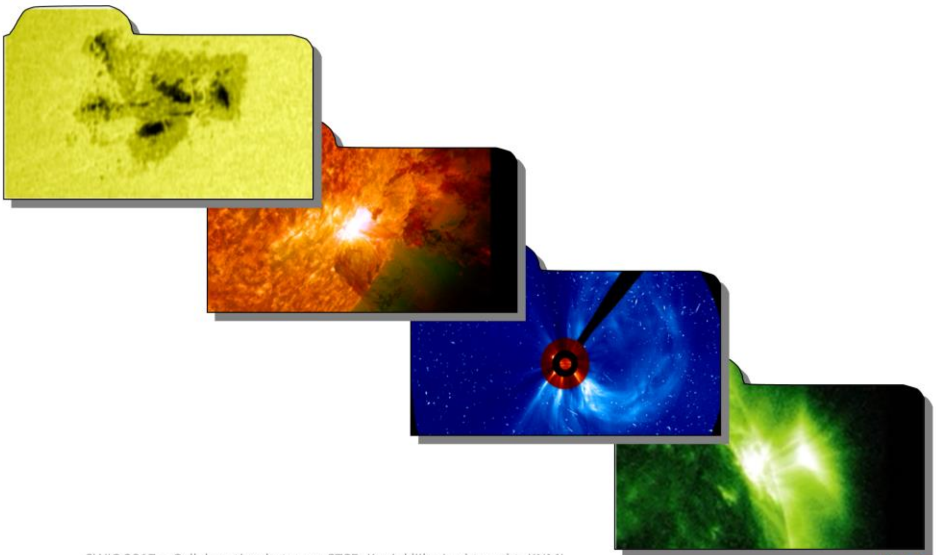








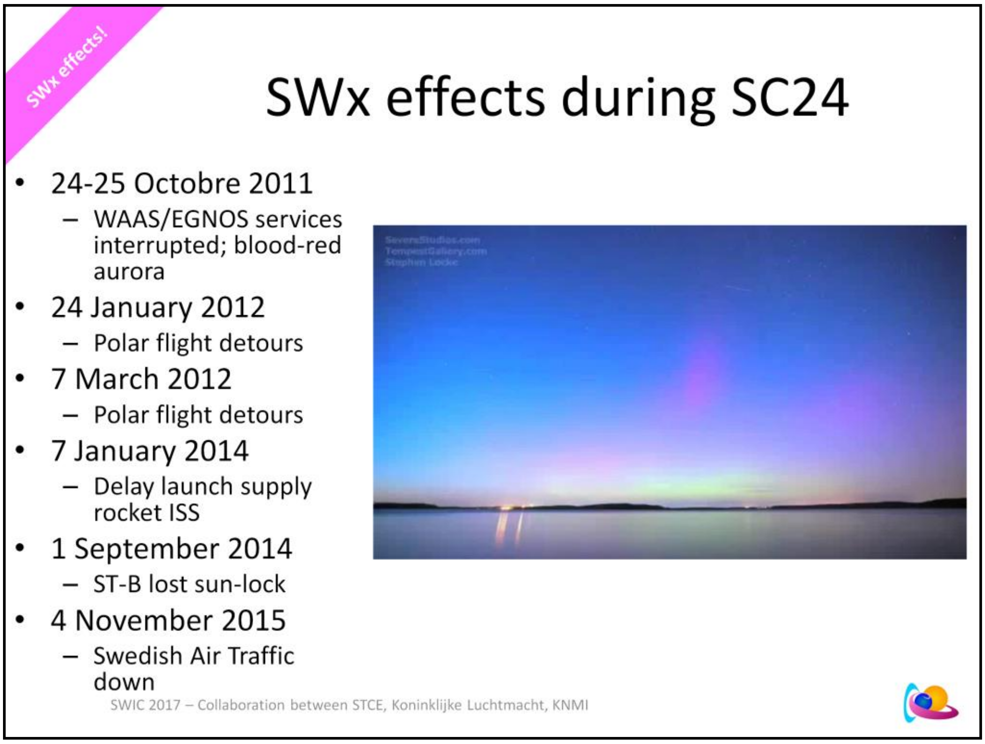
The big solar storms of SC24



Big solar storms during SC24…

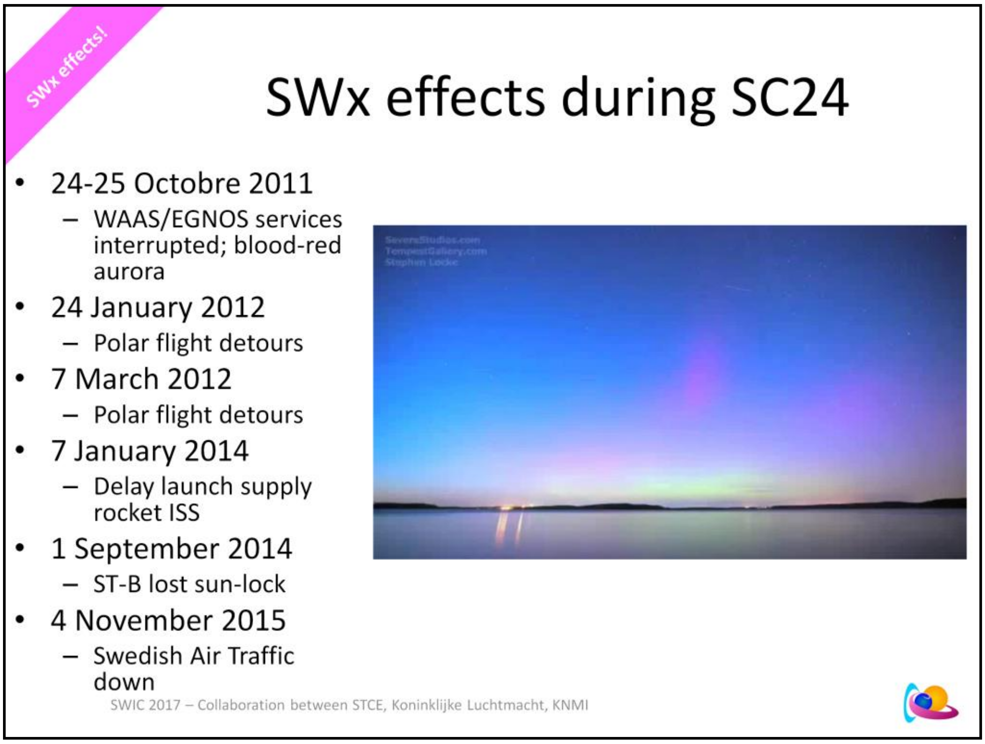
SWx effects!

Date event	NOAA R	NOAA S	NOAA G	Remarks
7 Jun 2011	1	1	-	Impressive eruption, NOAA 1226 (M2/72pfu)
3-4 Aug 2011	2	1	4	CME cannibalism; Aurora in NL, GE,… NOAA 1261 (M6/M9; 96pfu)
9 Aug 2011	3	1	-	Strongest flare of SC24 so far; NOAA 1263 (X6.9; 26pfu)
21-22 / 24-25 Oct 2011	1	-	3	GOES exposed; GIC; bloodred aurora in OK & AZ (USA), New-Z & Australia (M1/M1); WAAS/EGNOS!
23-24 Jan 2012	2	3	-	M8 LDE (6310 pfu) in NOAA 1402; several polar flights rerouted
7 Mar 2012	3	3	3+	Several SWx effects; NOAA 1429 (X5.4; 6530 pfu)
19 Jul 2012	2	-	-	Round post-flare coronal loops; NOAA 1520 (M7.7)
23 Jul 2012	Farside	1	Farside	FTE (19hrs): 3400 km/s; ; NOAA1520 (12 pfu); Carrington-like event
31 Aug 2012	-	1	1	Impressive filament eruption (C8; 59pfu)
29 Sep – 02 Oct 2013	-	2	4	Impressive filament eruption (C1; 182 pfu)
7 Jan 2014	3	3	-	NOAA 1944 (X1; 1033 pfu); Launch supply vessel ISS delayed
25 Feb 2014	3	2	2	NOAA 1990 (X4.9; 103 pfu)
1 Sep 2014	Farside	Enhanced	-	« NOAA2158 »; ST-A lost Sun-lock
10 Sep 2014	3	2	3	NOAA 2158 (X1; 126 pfu))
16-30 Oct 2014	3	-	-	NOAA 2192 (X1/X1/X3/X1/X2/X2); NO CMEs!
15 / 17 Mar 2015	-	-	4	Most intense G-storm of SC24 Dst -223nT ; NOAA 2297 (C9)
21-23 Jun 2015	2	3	4	NOAA 2371 (M7; 1070pfu); Dst: -204nT
4 Nov 2015	1	-	2	NOAA 2443 (M3.7); ATC Sweden out!



On 24-25 October 2011, another episode of major geomagnetic storming (Kp = 7 ; Dst = -147 nT) took place. The most likely source of the responsible CME seems to have been a filament eruption in the northwest solar quadrant early on 22 October. However, also the CMEs associated with the M1.3 eruption in NOAA 1319 on 21 October (peak at 13:00UT) and especially the long duration M1.3 flare in NOAA 1314 on 22 October (peak at 11:10UT) could have contributed. Space weather effects were numerous. The Earth's magnetic field got so compressed that geosynchronous satellites were briefly exposed to the solar wind. Geomagnetically induced currents were recorded in Scandinavia, and a Forbush decrease of 5.5% was recorded by neutron monitors on Earth (Oulu NM ; 5 min. data). The storm will especially be remembered for its blood red aurora, some of which were seen as far south as Oklahoma and Arizona, as well as in New Zealand and in Australia.
See STCE news itm: « The best of… 2011 » at http://www.stce.be/news/353/welcome.html

http://onlinelibrary.wiley.com/doi/10.1002/2013SW000982/epdf : Federal Aviation Administration's Wide Area Augmentation System (WAAS) navigation
service in the U.S.
Solar cycle 24 has brought about increased ionospheric activity and a handful of ionospheric storms that have affected aircraft navigation services so far. None of these storms has been rated as "extreme" according to the NOAA operational definition (*Kp* = 9). WAAS vertically guided approach (LPV, LPV200) availability has been reduced on several occasions, most significantly for the 24–25 October 2011 storm. During this event the nighttime onset of geomagnetic storming seems to be correlated with a nighttime persistent, corotating plume of enhanced TEC extending northwestward from Florida across CONUS. TEC time-varying imaging indicates that the plasma in this plume convected northwestward, which may help to explain its shape and duration of several hours. This nighttime plume caused a loss of navigation service for several hours in CONUS. After recovering service coverage over the entire region in the local morning, dayside activity on the 25th caused a second drop in vertically guided approach coverage, but it is less severe in extent and duration.



24 January 2012
http://www.nydailynews.com/news/delta-air-lines-reroutes-flights-concerns-big-solar-flare-article-1.1011344
Jan 23/0530Jan 24/1530 6310 Halo /23 0400 Jan 23/0359M8/long durationN28W3611402

Event 3: 7 March 2012 – X5.4 flare in NOAA 1429

The second largest x-ray flare so far this solar cycle was produced at midnight on 7 March 2012 by NOAA 1429. SDO white light images revealed this X5-flare was also a (very rare) white light flare. It was accompanied by the strongest proton storm so far in SC24 ("S3" on the NOAA-scale for radiation storms), and caused airlines to detour their polar flights for lack of communication. It was the largest proton signature registered by the Curiosity spacecraft which at that time was en route to Mars (see this STCE Newsletter). A plasma cloud was also ejected straight to Earth (full halo CME) and eventually resulted in a major geomagnetic storm on 9 March.
Solar flares (R3) : Only brief radio black-outs
Proton storm (S3) : Detour polar flights (Not for radiation, but communication), Astronauts safe, some satellite-instruments temporary down (ACE, VEX)
Geomagnetic storm (G3) : Polar light not spectacular (Not in Belgium), No influence on GPS, ISS,…
See also STCE newsitem "The fairest of them all… (2012)" at
http://www.stce.be/news/173/welcome.html

7-8 January 2014

From spaceweather.com:
ROCKET LAUNCH FOILED BY SOLAR ACTIVITY: Orbital Sciences Corp. scrubbed today's launch of their Antares supply rocket to the International Space Station in response to an ongoing solar radiation storm, described below. A launch at 1:10 p.m. EST Thursday is possible if the storm subsides.
http://www.space.com/24202-huge-solar-flare-delays-private-rocket-launch.html
See also the STCE newsitem "Stupendous NOAA 1944!" at
http://www.stce.be/news/232/welcome.html

SWx effects!

SWx effects during SC24

- 24-25 Octobre 2011
  - WAAS/EGNOS services interrupted; blood-red aurora
- 24 January 2012
  - Polar flight detours
- 7 March 2012
  - Polar flight detours
- 7 January 2014
  - Delay launch supply rocket ISS
- 1 September 2014
  - ST-B lost sun-lock
- 4 November 2015
  - Swedish Air Traffic down

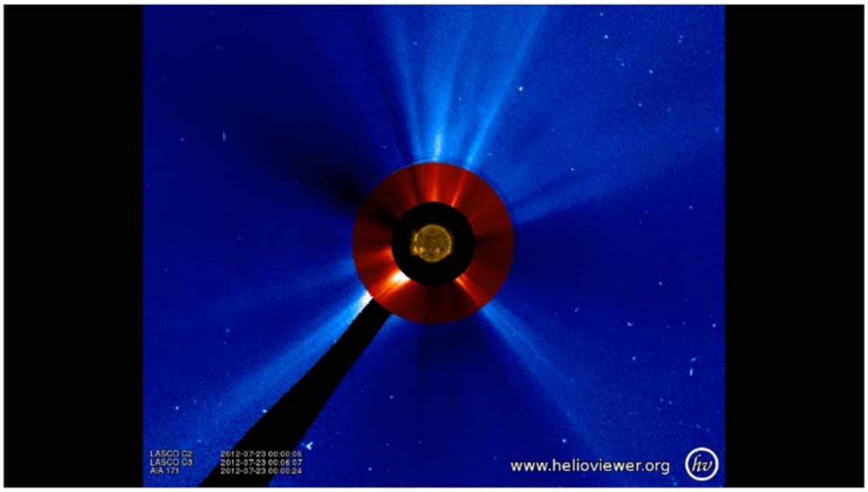
SWIC 2017 – Collaboration between STCE, Koninklijke Luchtmacht, KNMI

<u>Event 8: – 1 September 2014 - Strong backside eruption</u>
On 1 September, STEREO-B observed a strong flare in an active region on the backside of the Sun, estimated to be a low-level X-class flare. The flare is associated to a strong proton flux increase. Amazingly, so many particles were slamming into STEREO-B's camera pixels (creating the white dots in the images) that they saturated the star-trackers onboard the spacecraft, making them lose lock on the Sun for about 4 hours. This resulted in a not correct orientation of the solar images. The large number of particles would also enhance proton fluxes as observed on Earth, for more than a week!
See STCE news item of 9 September 2014 at http://www.stce.be/news/266/welcome.html

On **<u>4 November 2015</u>**, NOAA 2443 produced an M3.7 flare peaking at 13:39UT. This at first sight very normal flare was associated with strong radio and ionospheric disturbances that also affected radar and GPS frequencies. As a result, Swedish air traffic was halted for about an hour during the afternoon. The air traffic problems started at the most intense phase of the radio storm, and followed right on the heels of a minor geomagnetic storm caused by the high speed stream of a coronal hole. The CME associated with the M3 flare would cause a moderate (Kp = 6) geomagnetic storm during the first half of 7 November.
See STCE news item « Strong radio event on 04 November » at
http://www.stce.be/news/326/welcome.html

Farside solar eruption

23 July 2012 - Carrington-like event in NOAA 1520

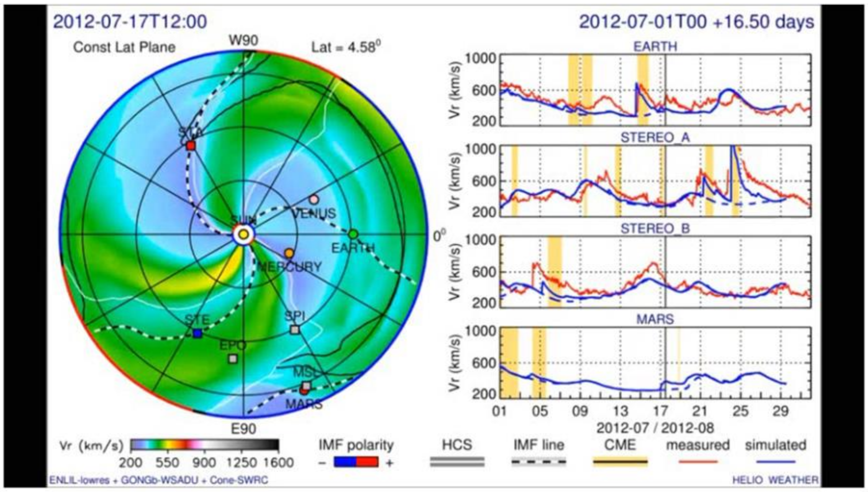


SWIC 2017 – Collaboration between STCE, Koninklijke Luchtmacht, KNMI

Description of the events at
STCE news item « A CME with an Olympic speed » at http://www.stce.be/news/152/welcome.html

Farside solar eruption

23 July 2012 - Carrington-like event in NOAA 1520



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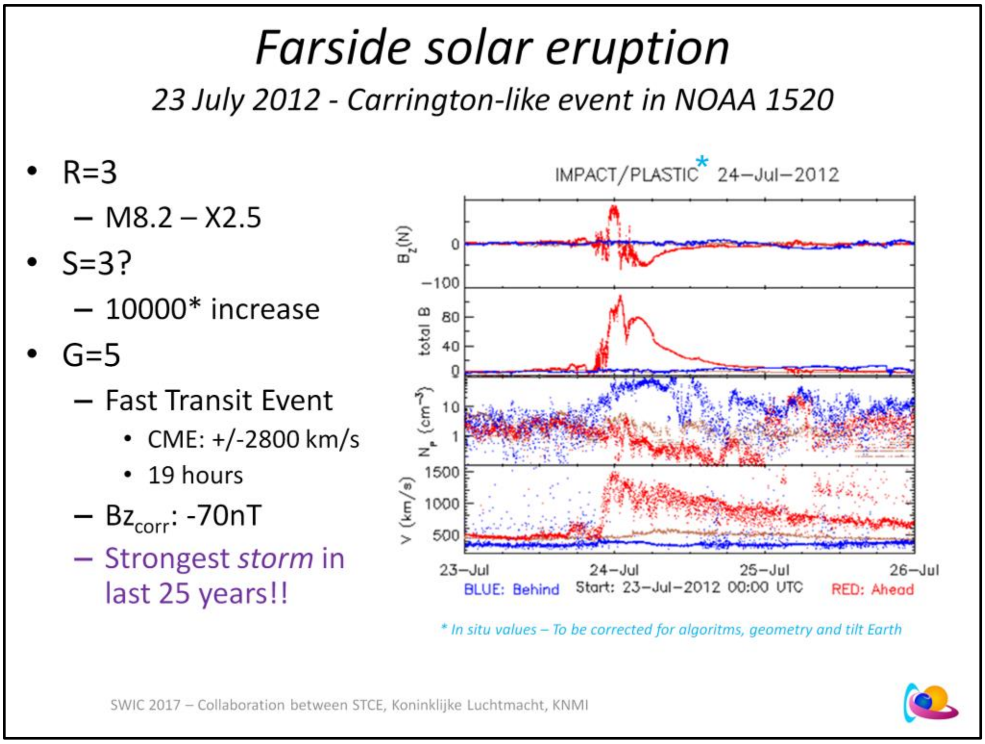
This movie is a cut from the original at http://helioweather.net/archive/2012/07/

ENLIL solar wind prediction at http://helioweather.net/



CME true speed of 2500 +/- 500 km/s

Baker et al. (2013): A major solar eruptive event in July 2012: Defining extreme space weather scenarios
http://adsabs.harvard.edu/abs/2013SpWea..11..585B
The key goal for space weather studies is to define severe and extreme conditions that might plausibly afflict human technology. On 23 July 2012, solar active region 1520 (~141°W heliographic longitude) gave rise to a powerful coronal mass ejection (CME) with an initial speed that was determined to be 2500 ± 500 km/s. The eruption was directed away from Earth toward 125°W longitude. STEREO-A sensors detected the CME arrival only about 19 h later and made in situ measurements of the solar wind and interplanetary magnetic field. In this paper, we address the question of what would have happened if this powerful interplanetary event had been Earthward directed. Using a well-proven geomagnetic storm forecast model, we find that the 23-24 July event would certainly have produced a geomagnetic storm that was comparable to the largest events of the twentieth century (Dst ~ -500 nT). Using plausible assumptions about seasonal and time-of-day orientation of the Earth's magnetic dipole, the most extreme modeled value of storm-time disturbance would have been Dst = -1182 nT. This is considerably larger than estimates for the famous Carrington storm of 1859. This finding has far reaching implications because it demonstrates that extreme space weather conditions such as those during March of 1989 or September of 1859 can happen even during a modest solar activity cycle such as the one presently underway. We argue that this extreme event should immediately be employed by the space weather community to model severe space weather effects on technological systems such as the electric power grid.

Figure generated from the Stereo website:
https://stereo-ssc.nascom.nasa.gov/browse/2012/07/24/insitu_3day.shtml